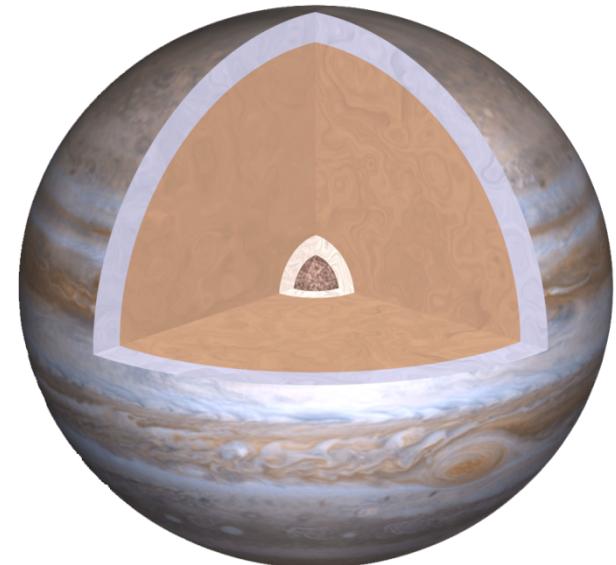


Diamond at 50 Mbar

**Thomas Duffy (Princeton) Ray Smith, Jon Eggert, Dave Braun,
Reed Patterson, Peter Celliers, Rip Collins (LLNL),
Jue Wang (Princeton) and Raymond Jeanloz (UC Berkeley)**

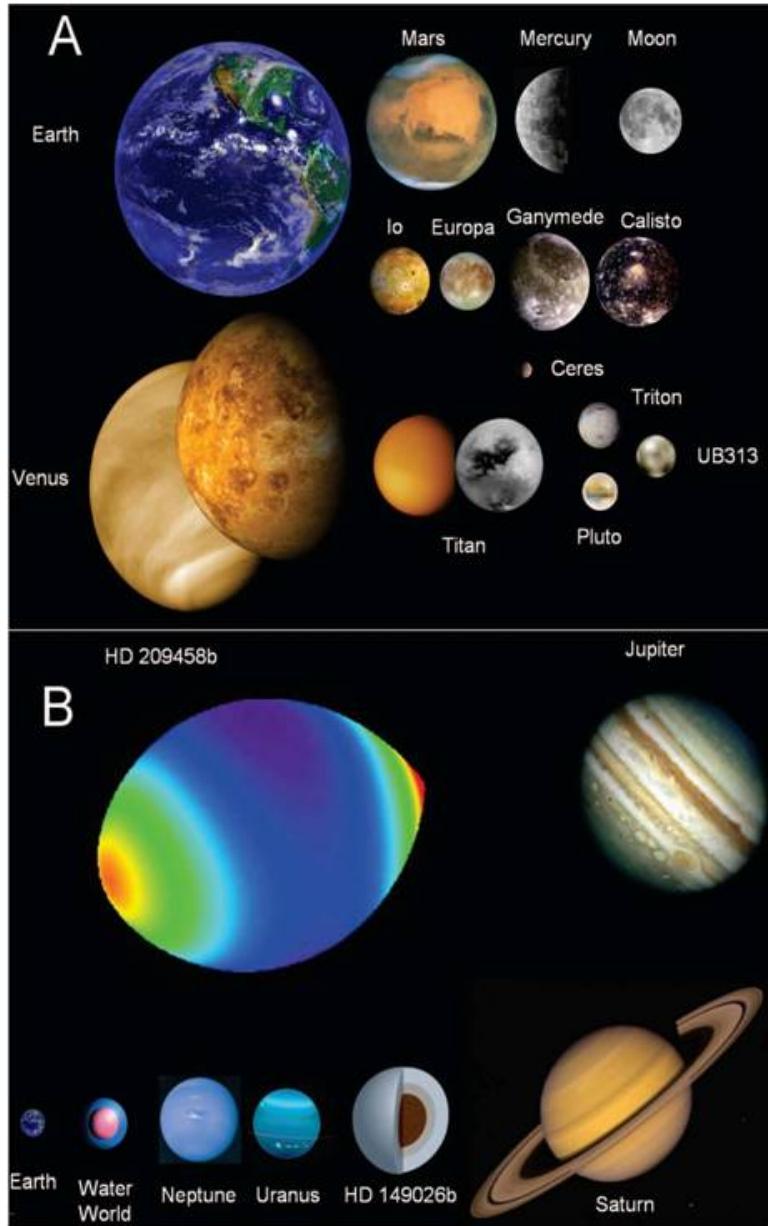
Generating planetary core
conditions with NIF



We acknowledge the contributions of the NIF Staff and Target Fabrication Team at LLNL

Key Questions About Planets Inside and Outside the Solar System

- What is the nature of the iron core at the center of Earth and other terrestrial planets?
- What are the interior structures of Jupiter, Neptune and the other giant planets?
- What kinds of planets exist outside our solar system? Can we characterize their structure, composition, dynamics and evolution?
- How do different types of planetary systems form and what are the implications for the origin and evolution of solar systems?



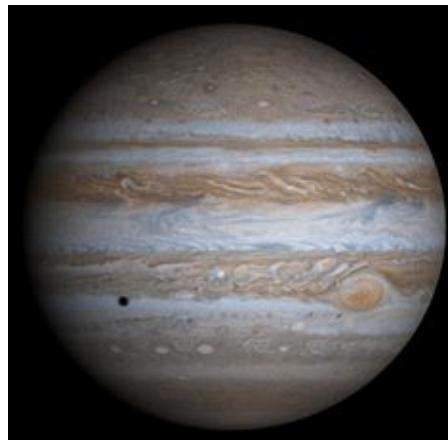
Planetary Pressures

P=Force/Area

$$1 \text{ GPa} = 10^9 \text{ N/m}^2$$

$$1 \text{ bar} = 10^{-4} \text{ GPa}$$

$$1 \text{ Mbar} = 100 \text{ GPa}$$



70 Mbar

← Center of Jupiter



40 Mbar

← Center of Saturn

30 Mbar

← Center of 10 Earth
Mass Planet

Core mantle
boundary



1.36 Mbar

Top of lower
mantle

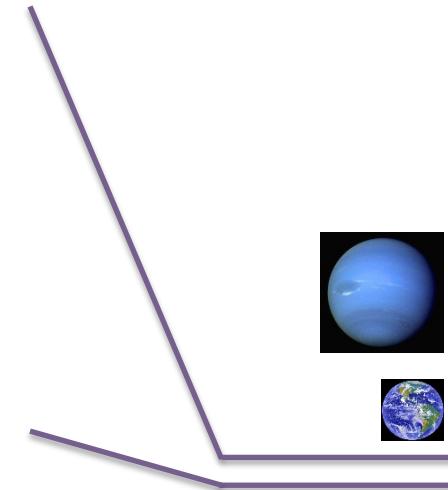


0.24 Mbar

Base of Earth's
crust



0.02 Mbar

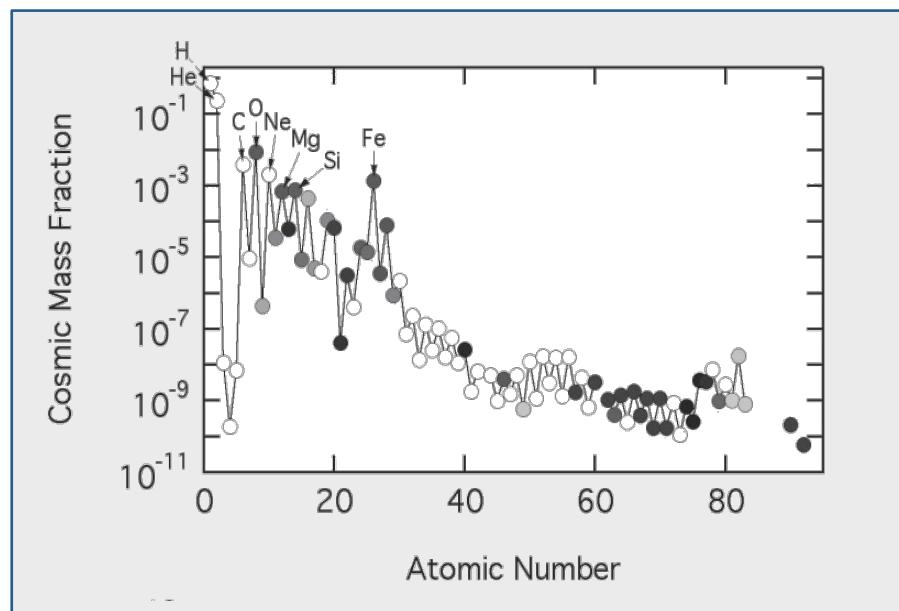


8 Mbar

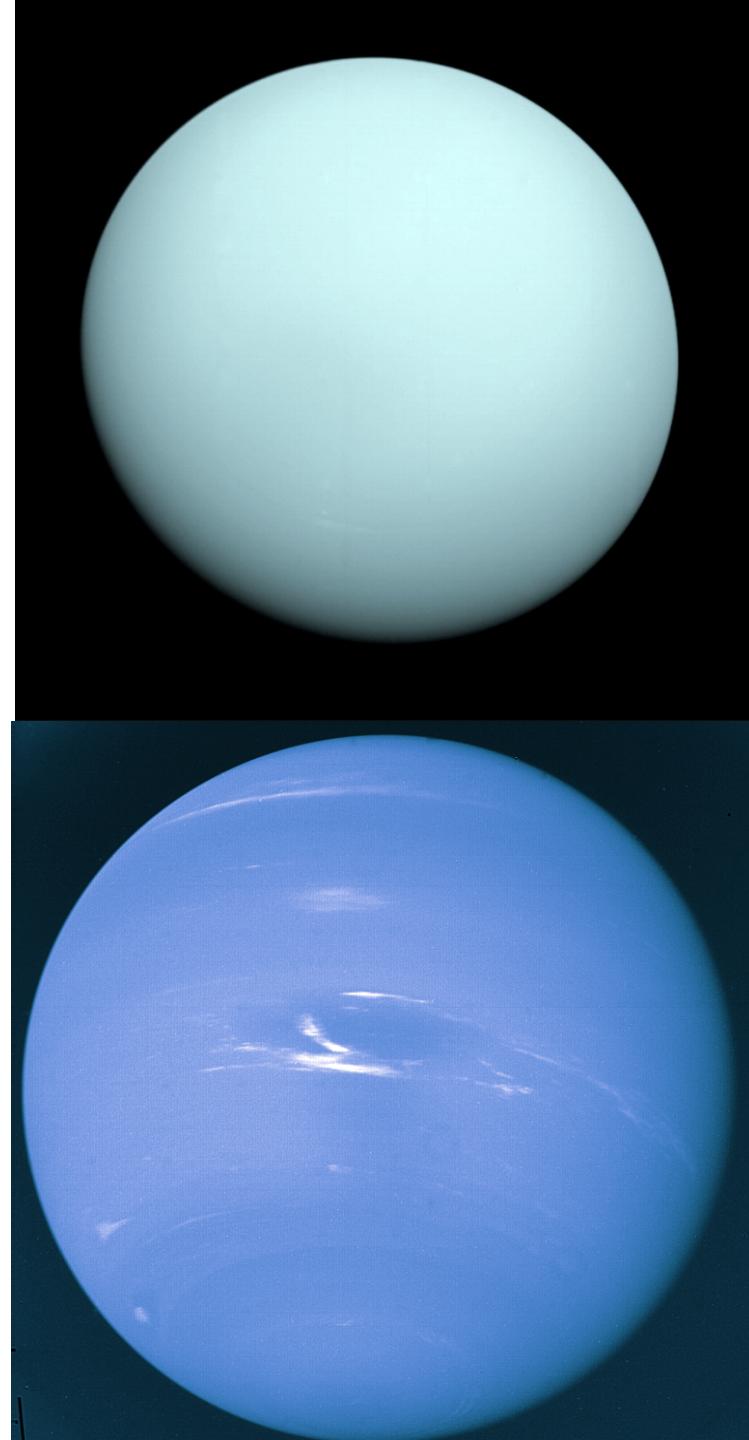
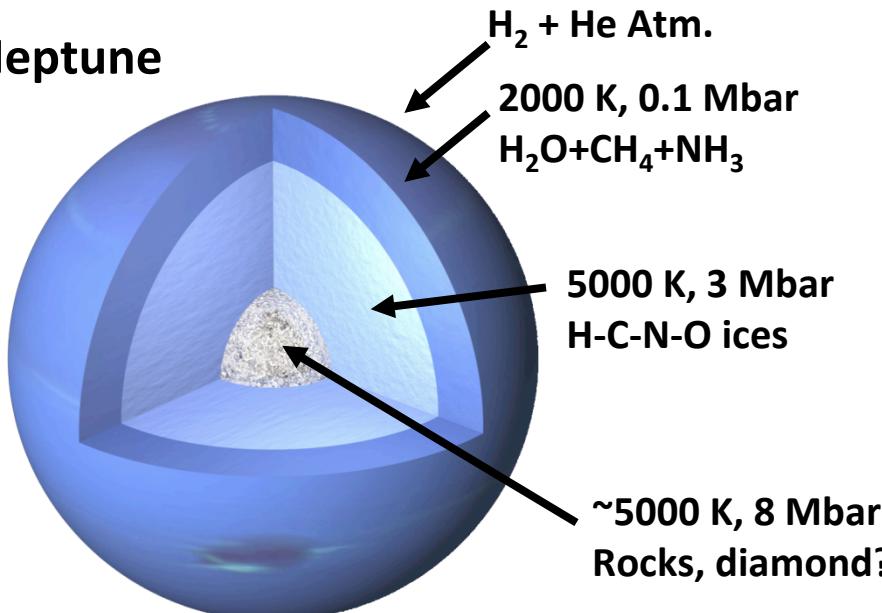
3.63 Mbar

← DAC Limit
← Center of Neptune
← Center of Earth

Carbon is the fourth most abundant element in the Cosmos



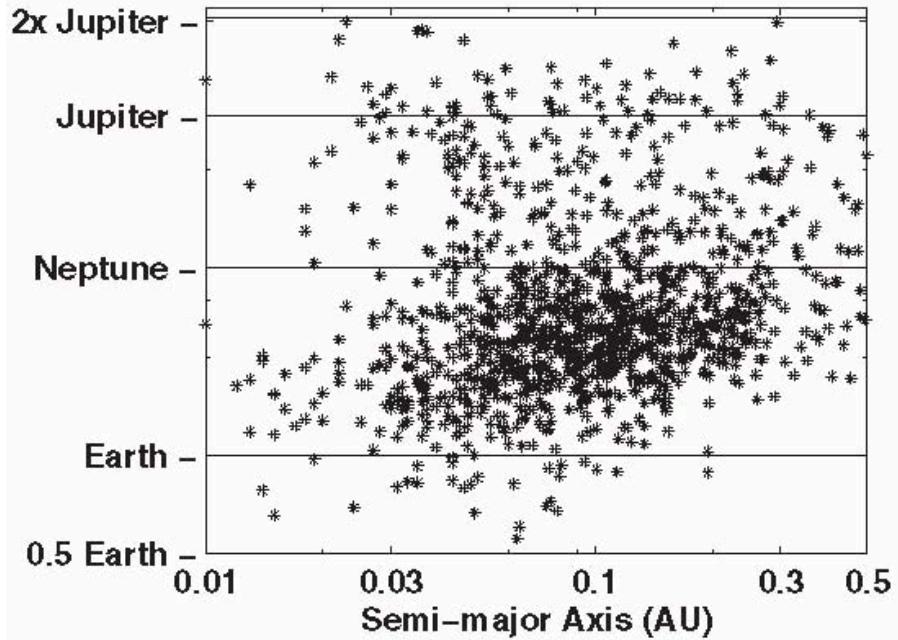
Neptune



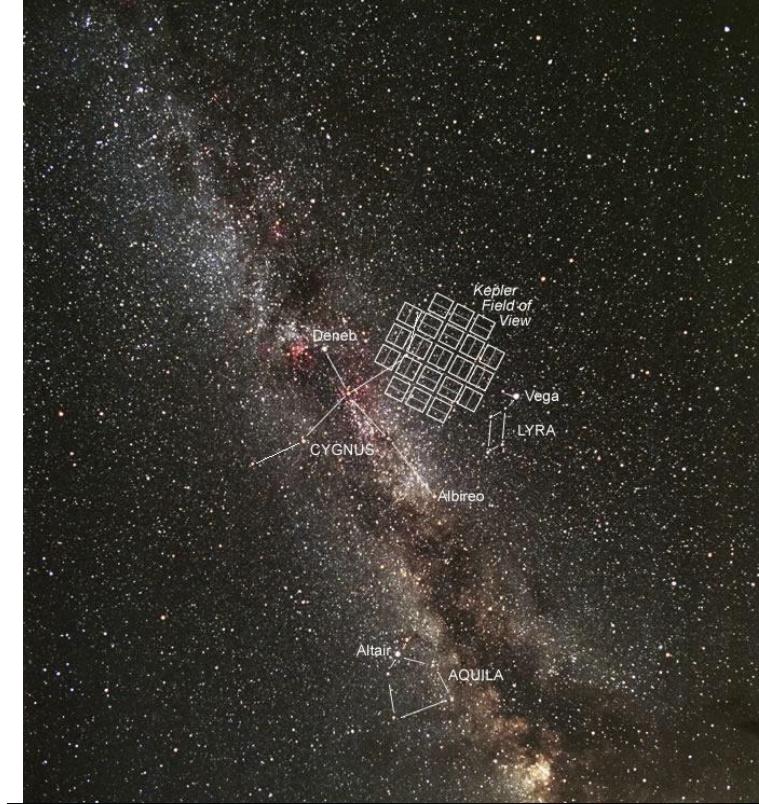
Neptune-sized planets are common in our galaxy

Kepler Mission: Searching for Transits over 15,000 Stars Simultaneously

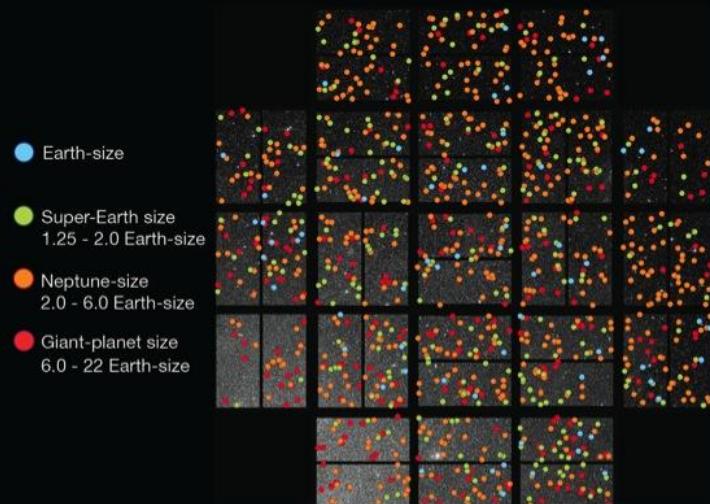
Size Distribution of Kepler Candidate Planets



~20% of stars have Neptune-sized planet

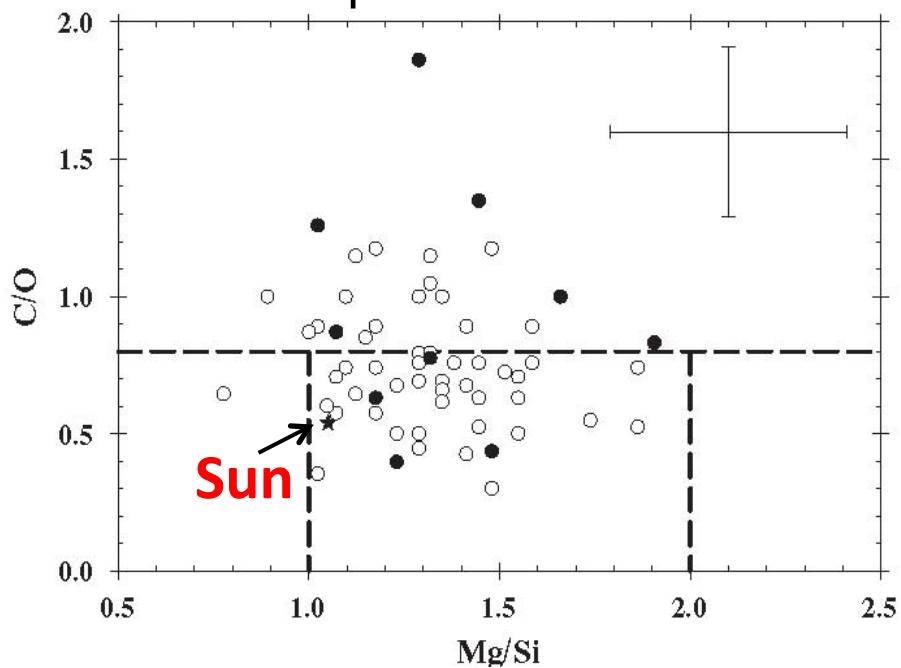


Locations of Kepler Planet Candidates



Carbon-rich Planets?

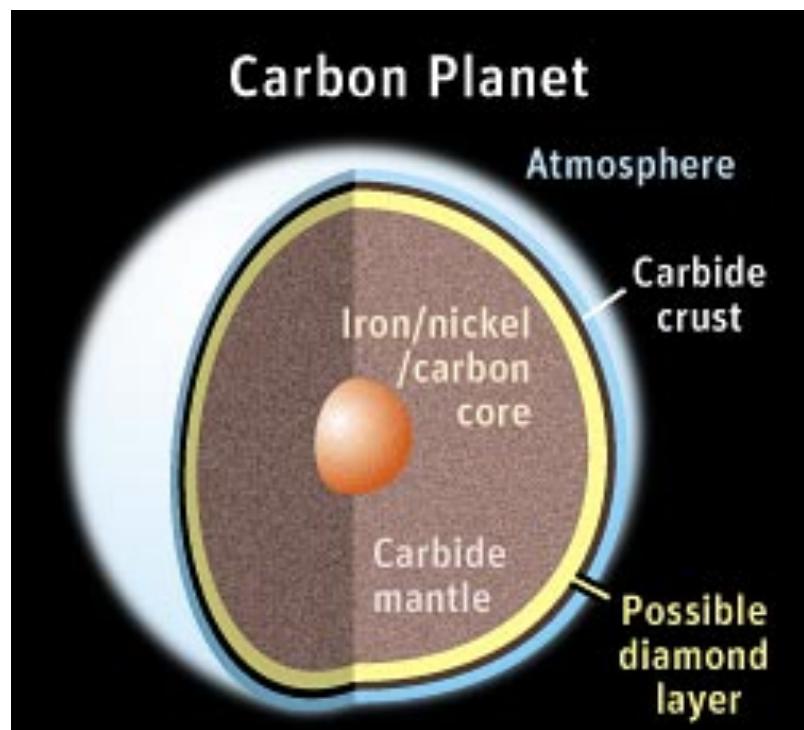
Measured C/O ratios
for exoplanet host stars



About 30% of host stars have C/O>0.8

IR spectroscopy of some protoplanetary disks show presence of nano-diamonds

If C/O < 0.8, Si \rightarrow silicates
If C/O > 0.8 Si \rightarrow carbides, solid C



Gaidos 2000
Kuchner & Seager 2005

Interior Structure and Evolution of Extra-Solar Planets

Interior structure inferred from mass-radius relationships
(supplemented by other observed properties)

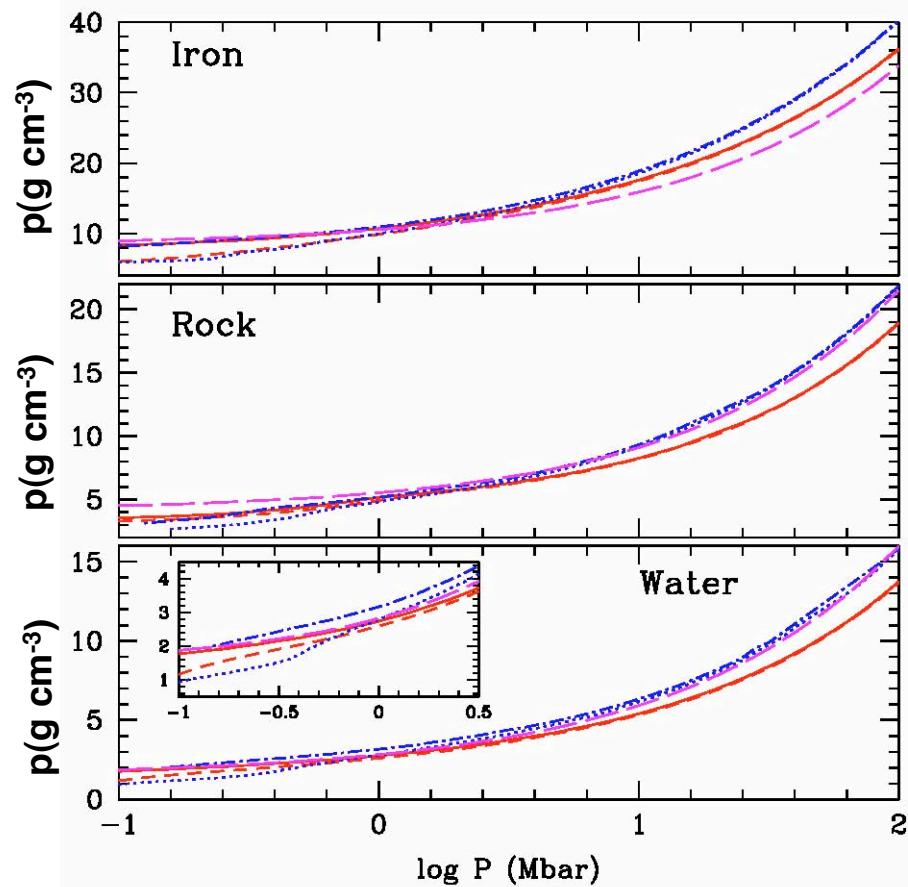
Equation of state (EOS) is needed to characterize the thermodynamic properties of planetary components

“Exploring the EOS of heavy material in the critical pressure regime 0.1–100 Mbar and at high temperature is crucial....in order to make progress in the thriving field of exoplanet exploration.”

Baraffe et al., 2008

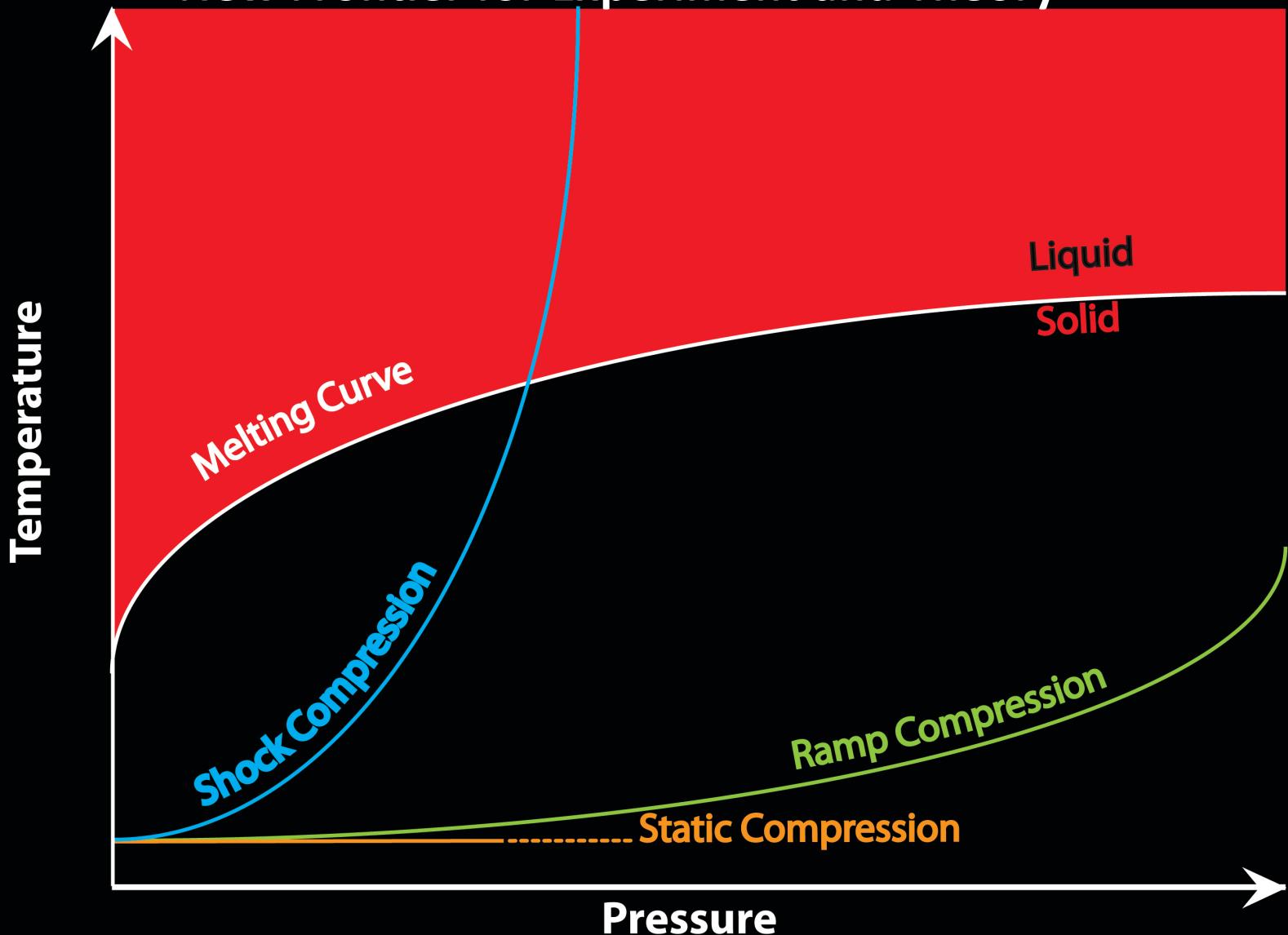
SuperEarth extrasolar planets achieve large pressures, up to ~60 Mbar where current equations of state are being extrapolated without any experimental data to constrain them.

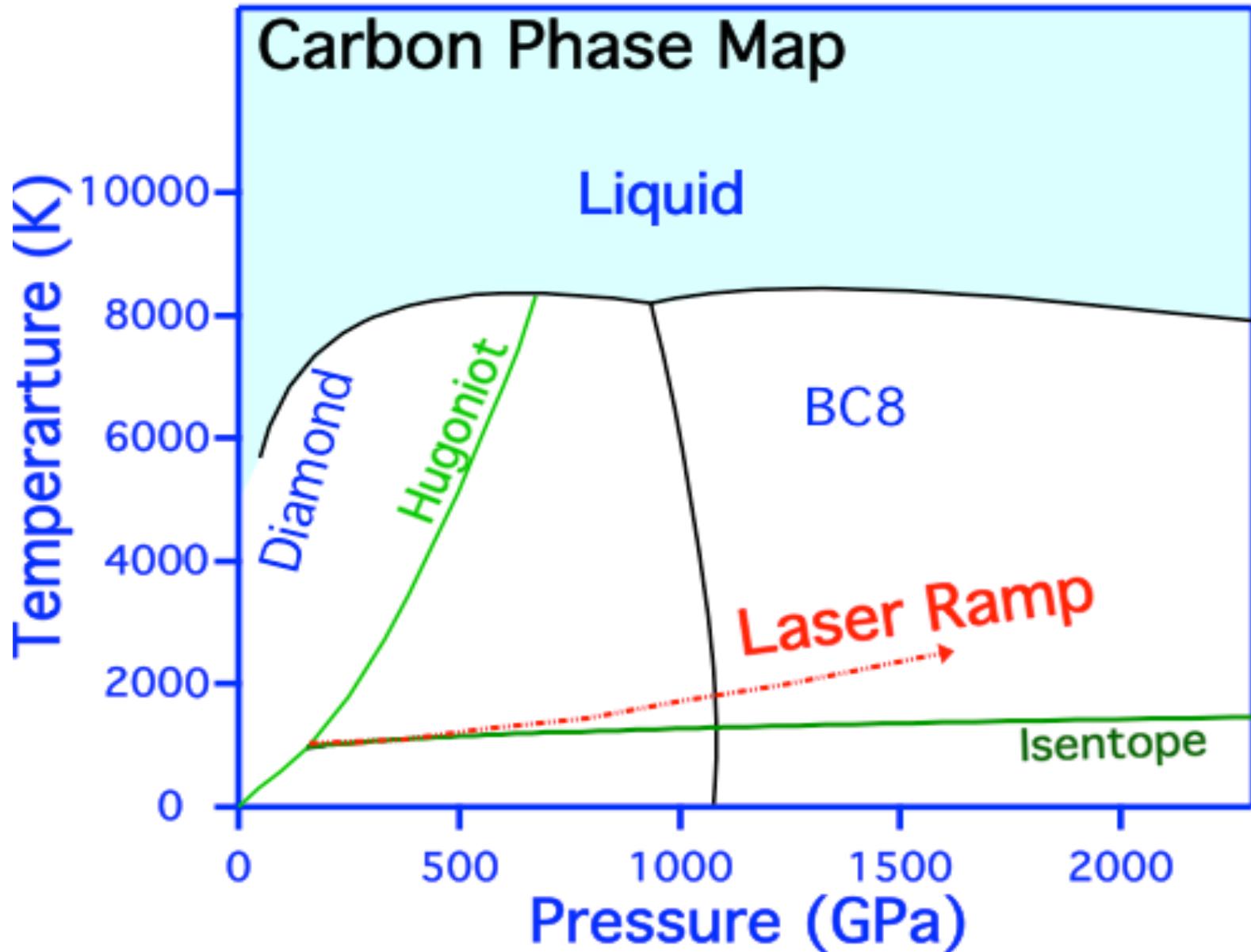
Valencia et al. 2009



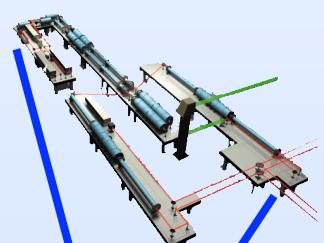
Baraffe et al. (2008)

Ultrahigh Pressure Solids via Ramp Compression: New Frontier for Experiment and Theory





Laser Facilities



Janus
Lawrence
Livermore
National
Lab
(CA)

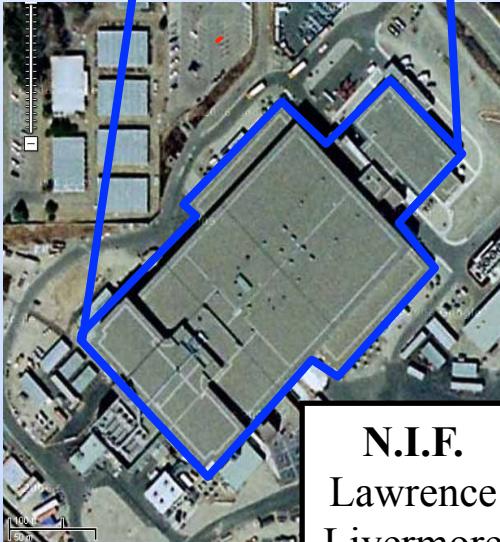
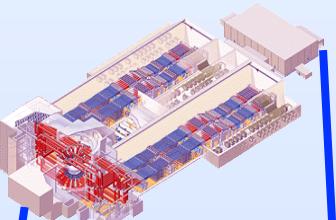
100
meters



Omega
University
of
Rochester
(NY)

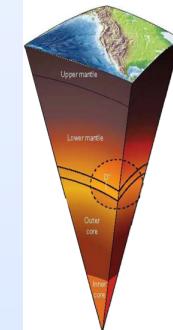
2 beam
1 kJ

60
Beams
30 kJ



192
Beams,
2 MJ
500 TW

N.I.F.
Lawrence
Livermore
National
Lab



Janus
DAC (3.5 Mbar)
Z-machine (3.8 Mbar)

Z-machine (3.8 Mbar)

LLE (8 Mbar)

**NIF Shots
(50Mbar)**

Diamond Targets for NIF Experiments

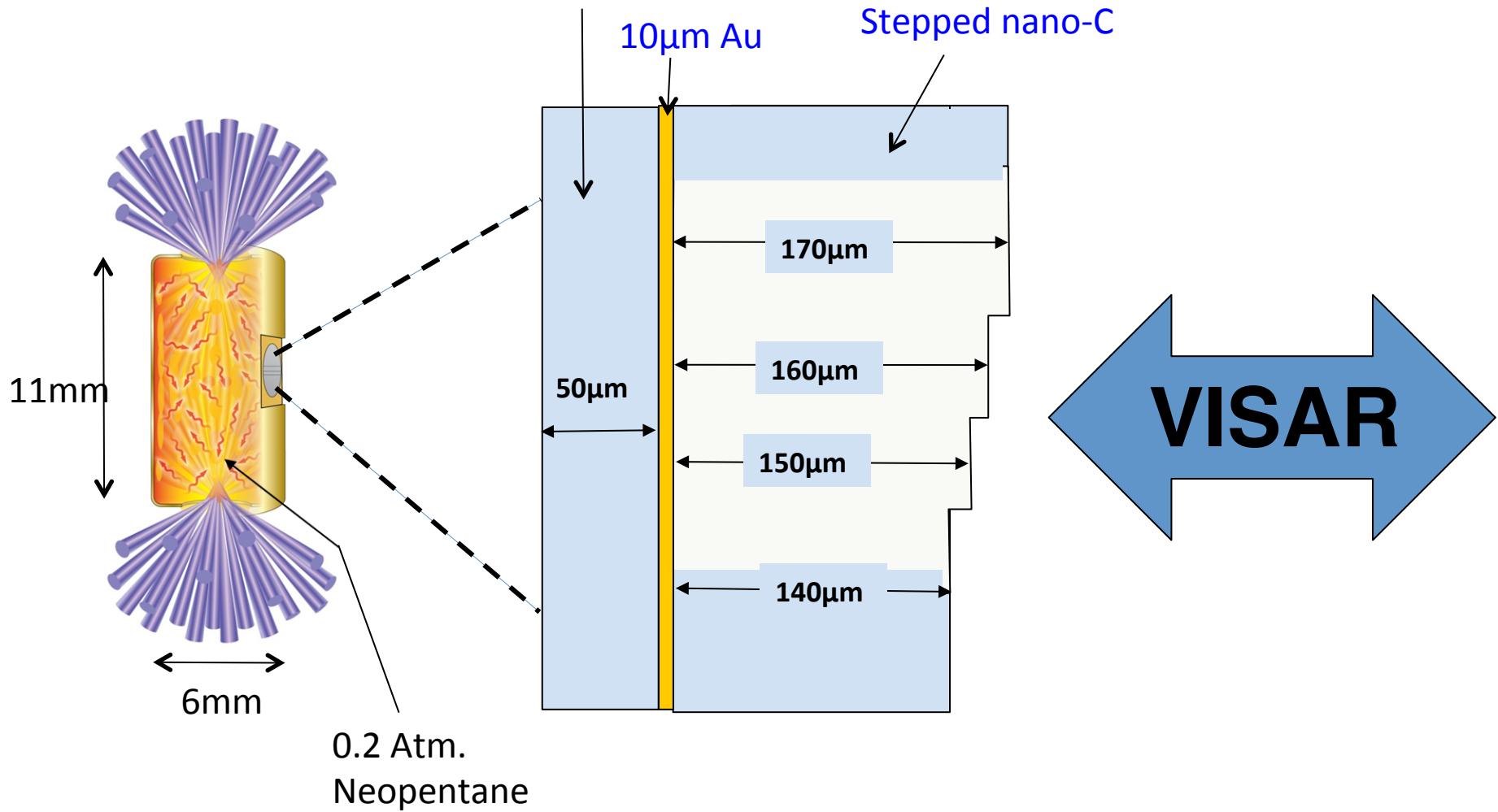
Stepped target, 10 μm step heights

CVD

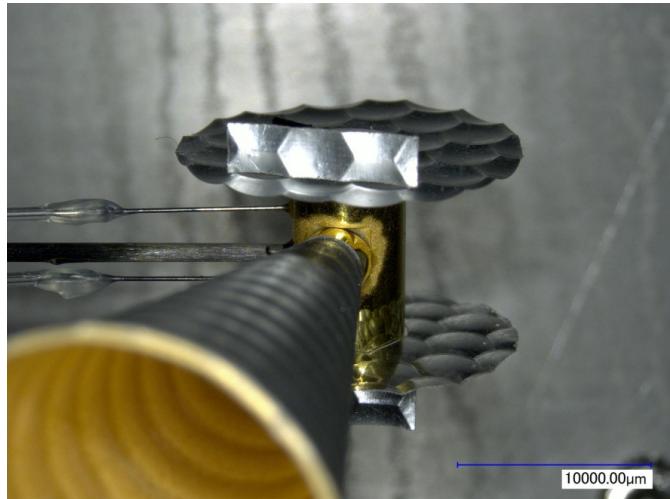
Nanocrystalline diamond (avg. grain size $\sim 200 \text{ nm}$)

3.25 gm/cm³, 7.6% porous

nano-C Ablator

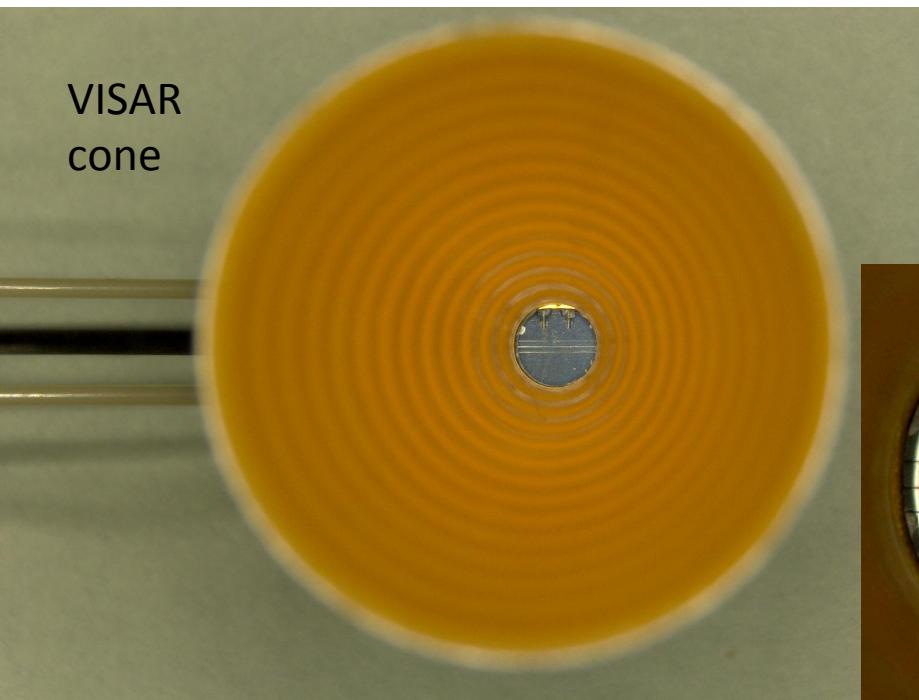


University Use EOS target: UUNIFEOS-C-11B-02

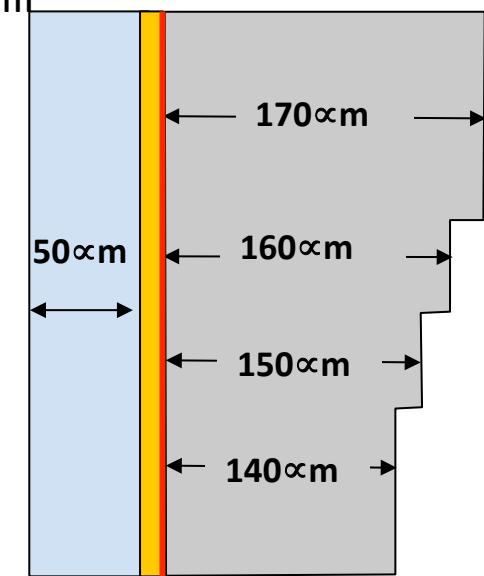
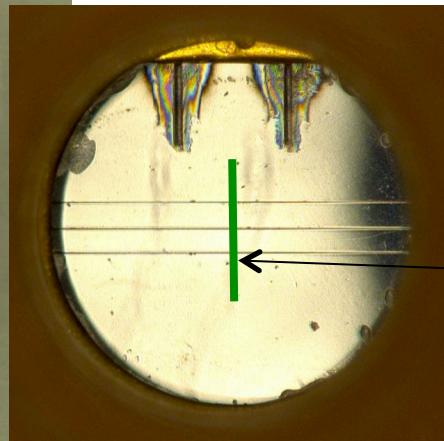


Gas-filled, room-temperature, stepped target mounted on side of Hohlraum with VISAR cone.

- 0.2 atm. Neopentane gas fill
- $L = 11$ mm
- $\phi = 6$ mm
- $LEH = 4.5$ mm.

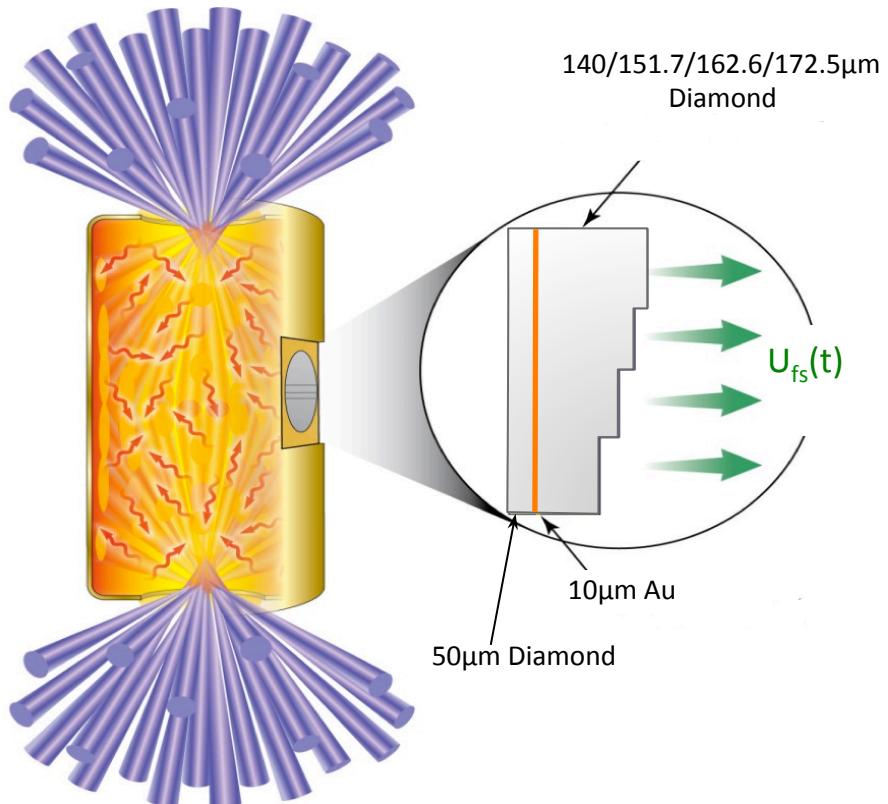


Dimpled shields protect from unconverted light



Line VISAR
Field-of-View, ~1mm

Laser Compression



--Laser beams heat walls of gold hohlraum

--Hohlraum acts as blackbody source emitting X-rays

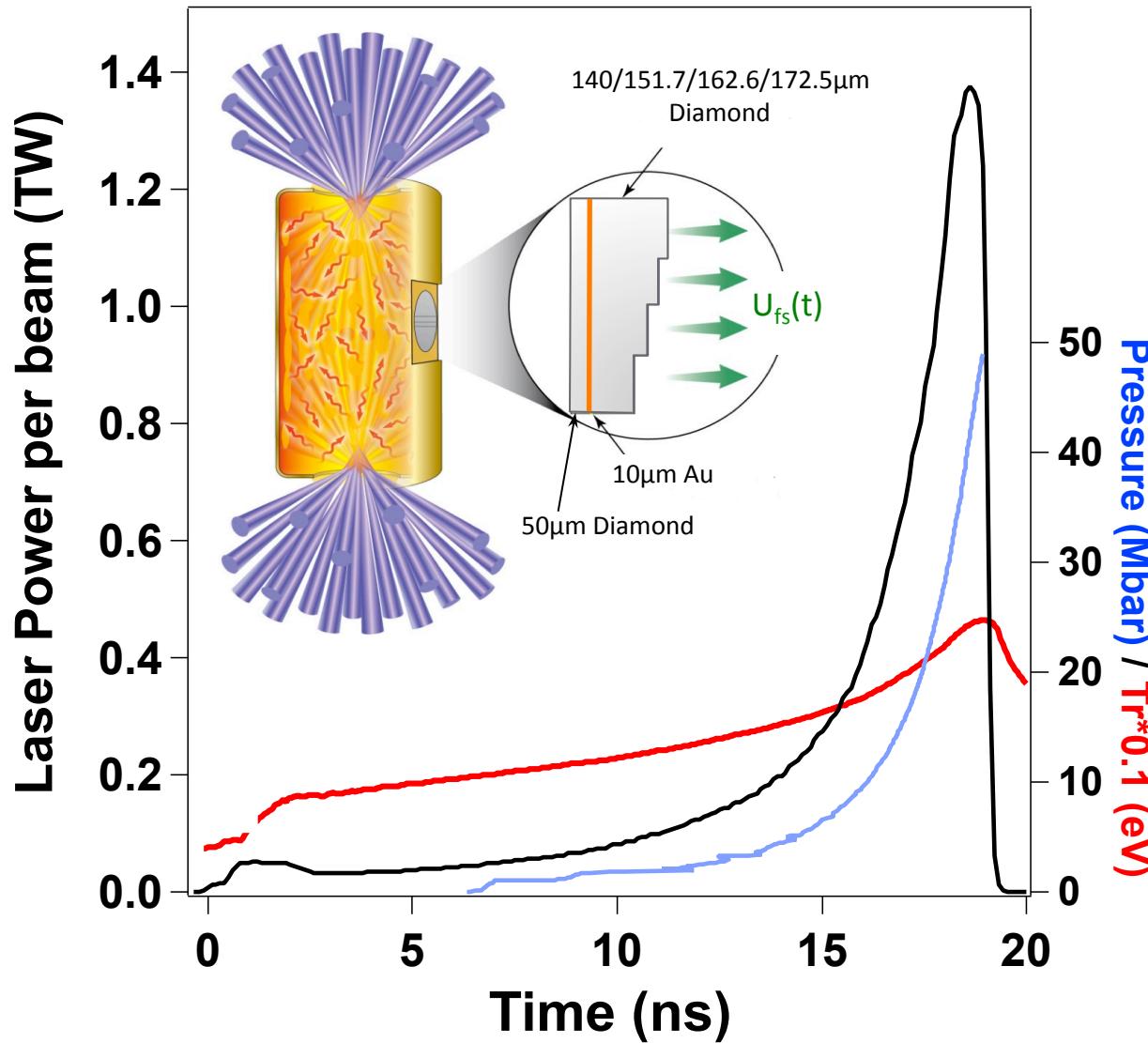
--X-rays ablate rear surface of target and counter-propagating ramp compression wave is launched into sample

--Four shots on diamond were conducted on NIF in 2011, with peak pressures from 22-50 Mbar.

Compression wave is adiabatic
Pulseshape and target determine if compression is a shock or ramp

Pulse Shape for NIF Experiments

176 beams of NIF were used to deliver a 20-ns ramp-shaped pulse with energies up to 0.76 MJ onto the inner walls of the Au hohlraum.



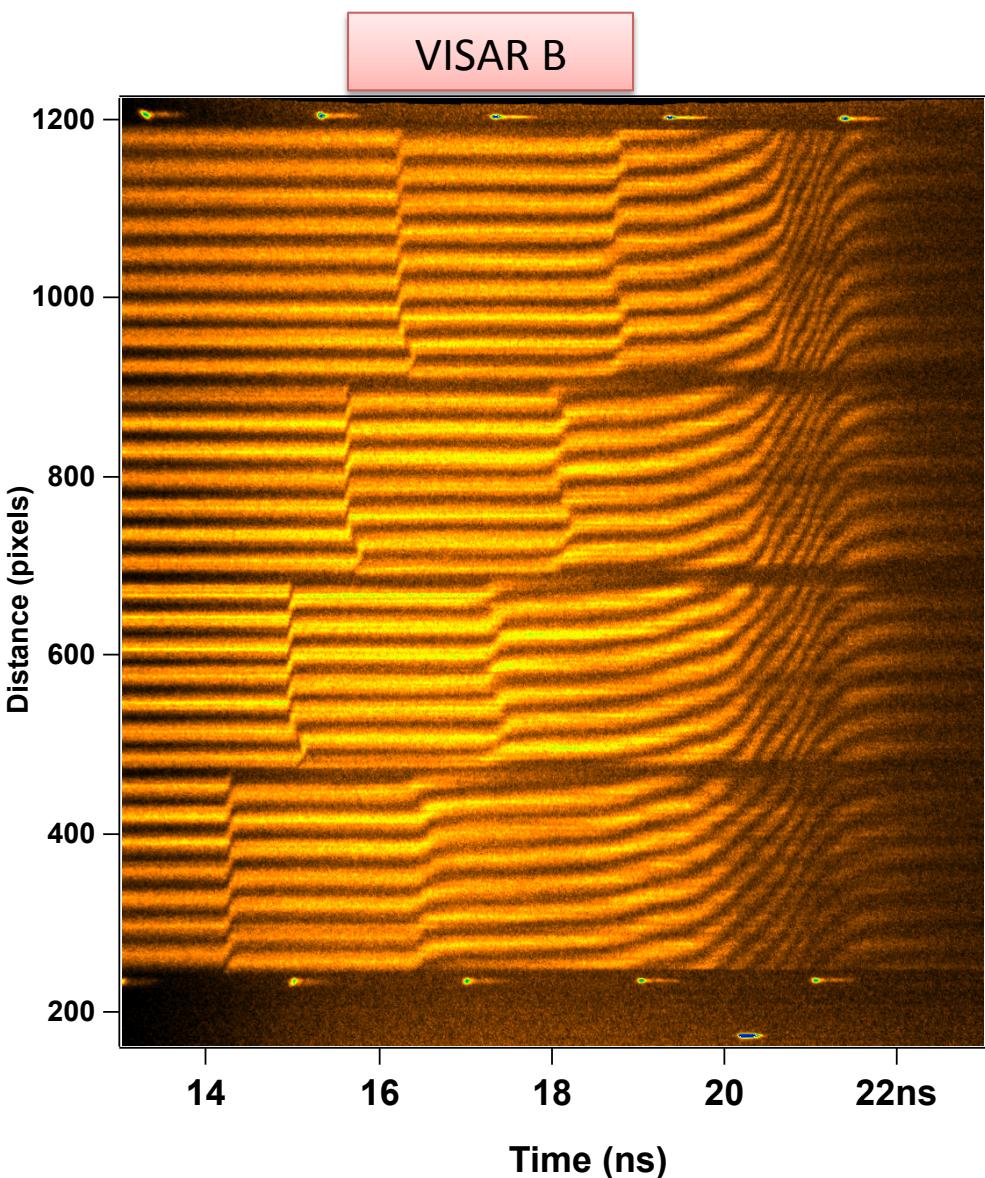
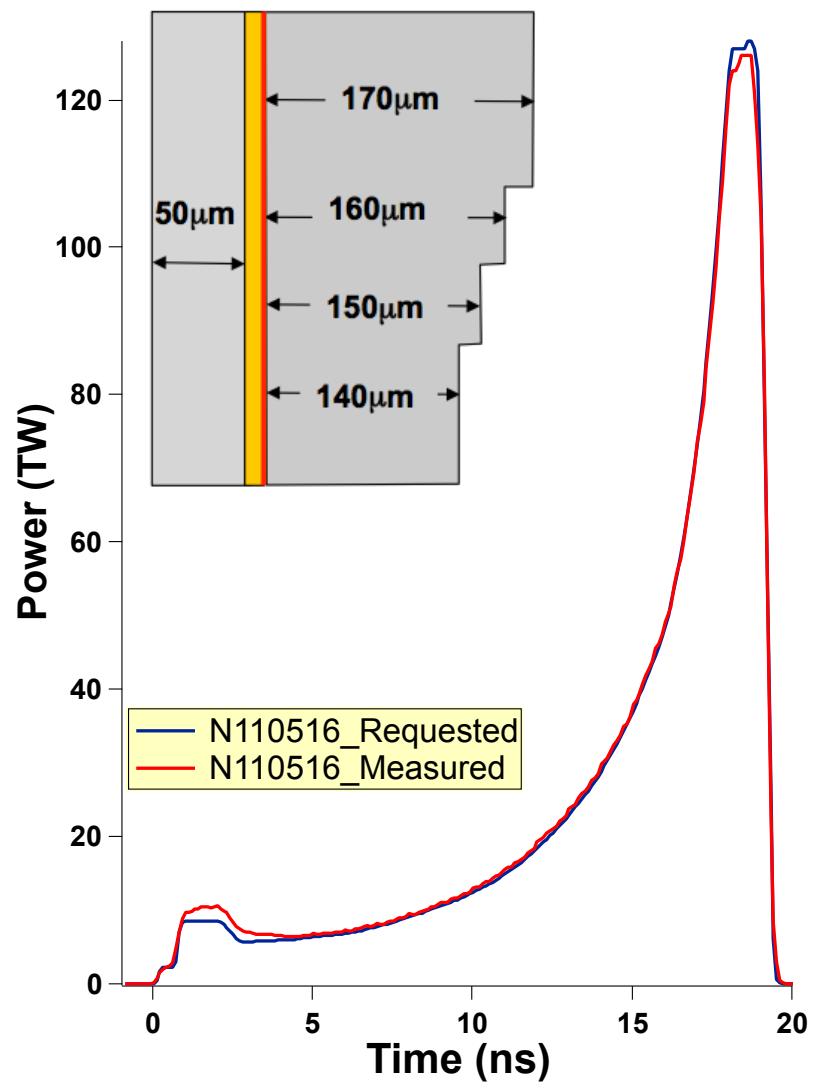
Shot N110524

Pressure – from
Lagrangian
analysis

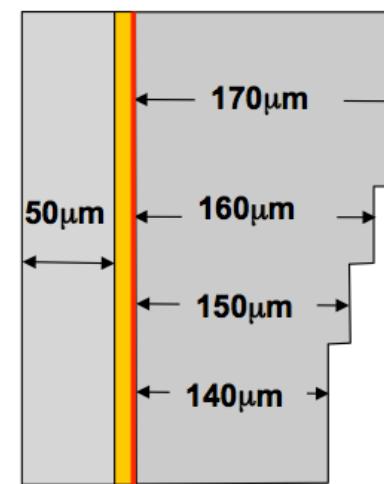
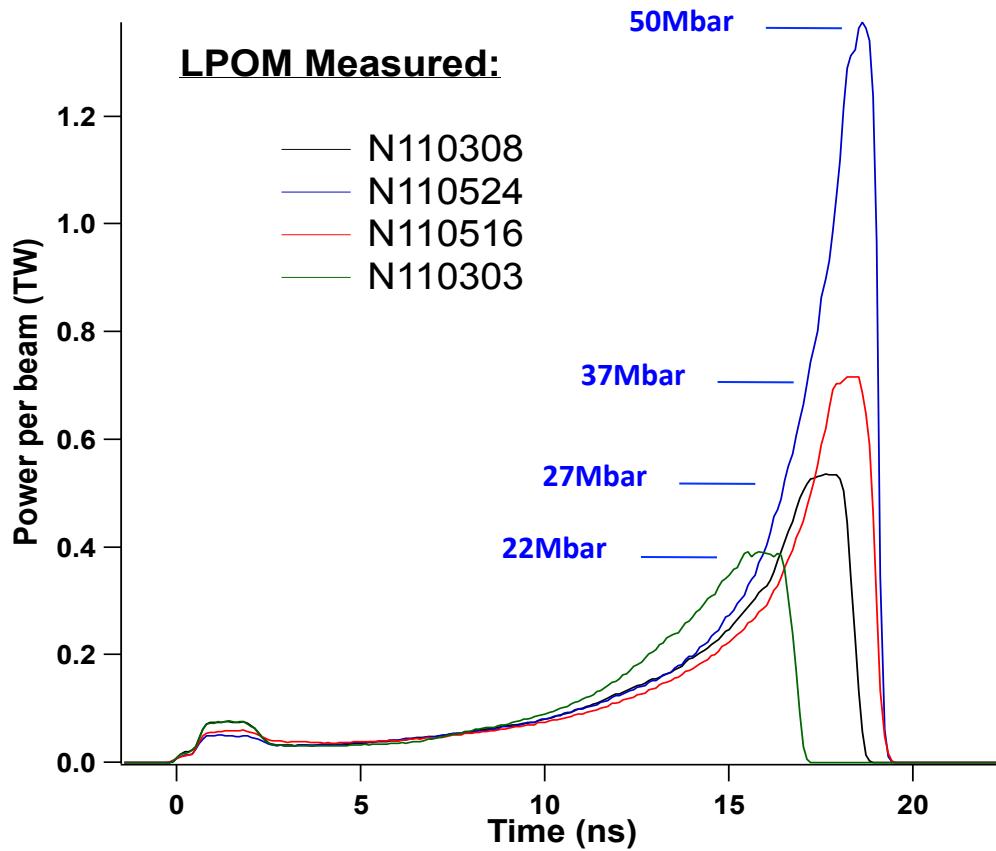
T_{r} =
Characteristic
temperature of
the X-ray drive

Peak: 245 eV

Requested vs. Measured Pulse shape at NIF

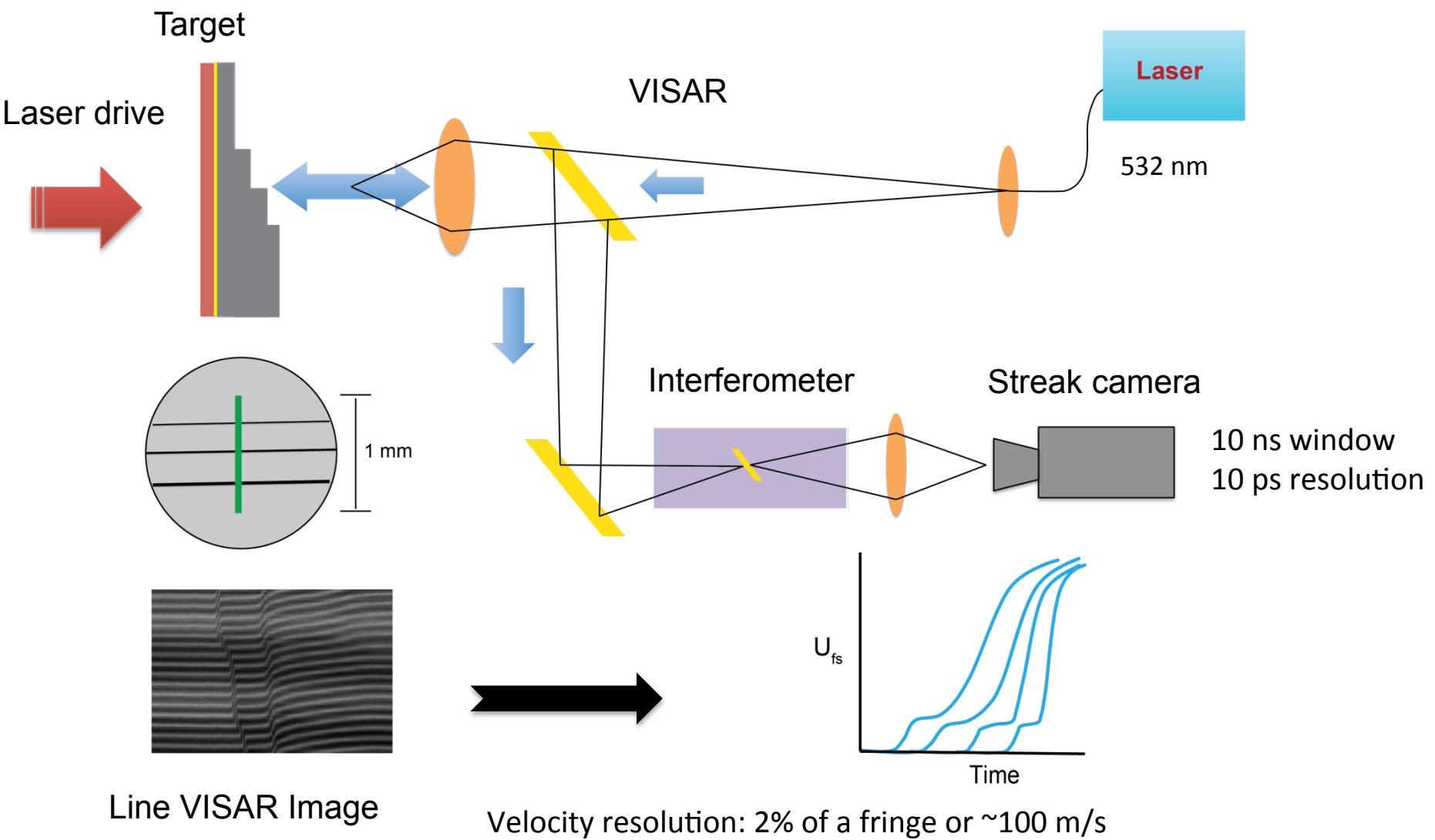


Pulse Shape for four NIF experiments on diamond



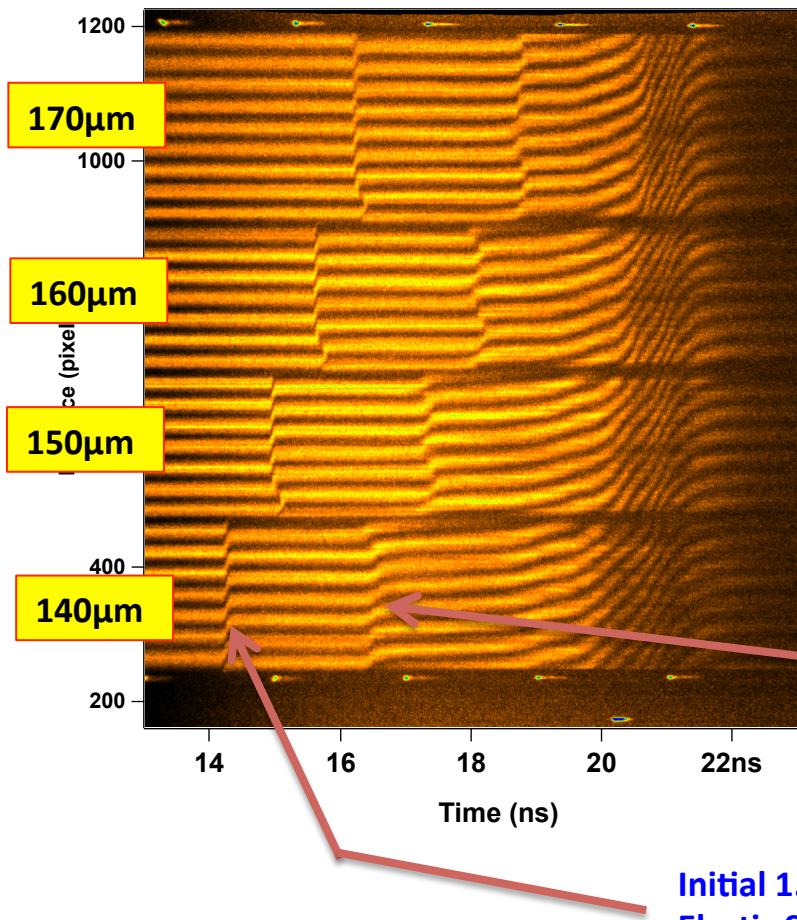
Line VISAR – Measures velocity across the rear surface of the target

Changes in free surface velocity produce phase shifts in interference fringes that are recorded by a streak camera

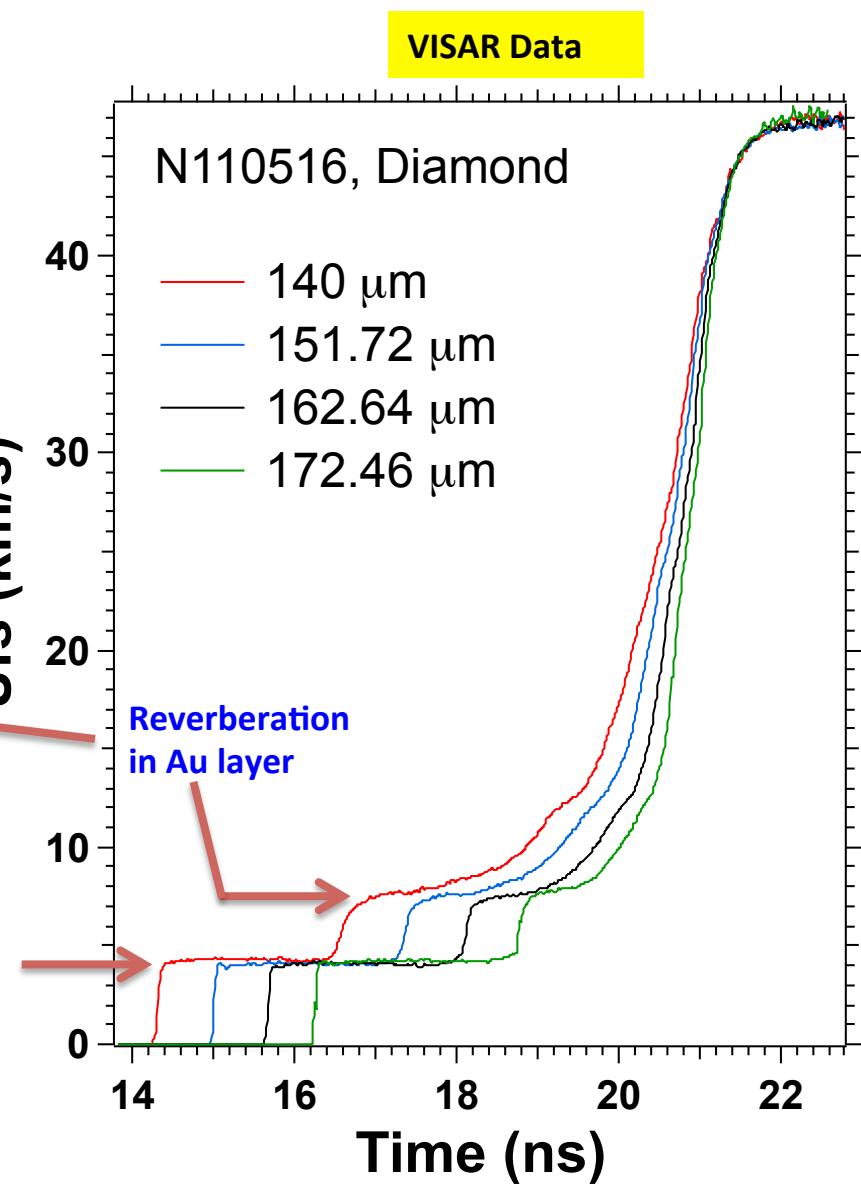


Diamond Ramp Compression: Results

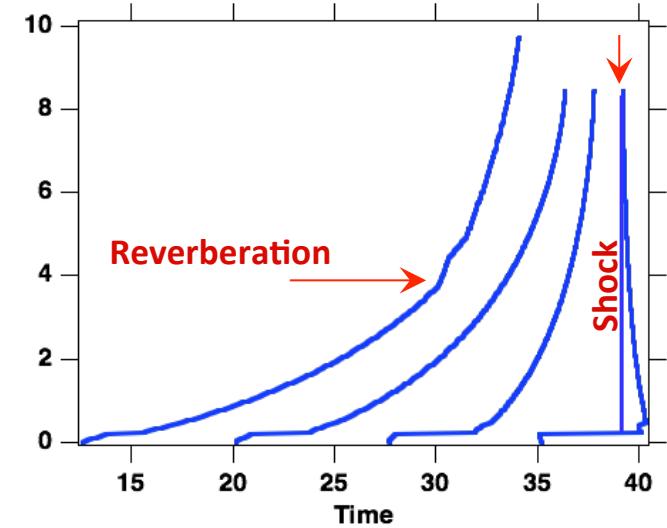
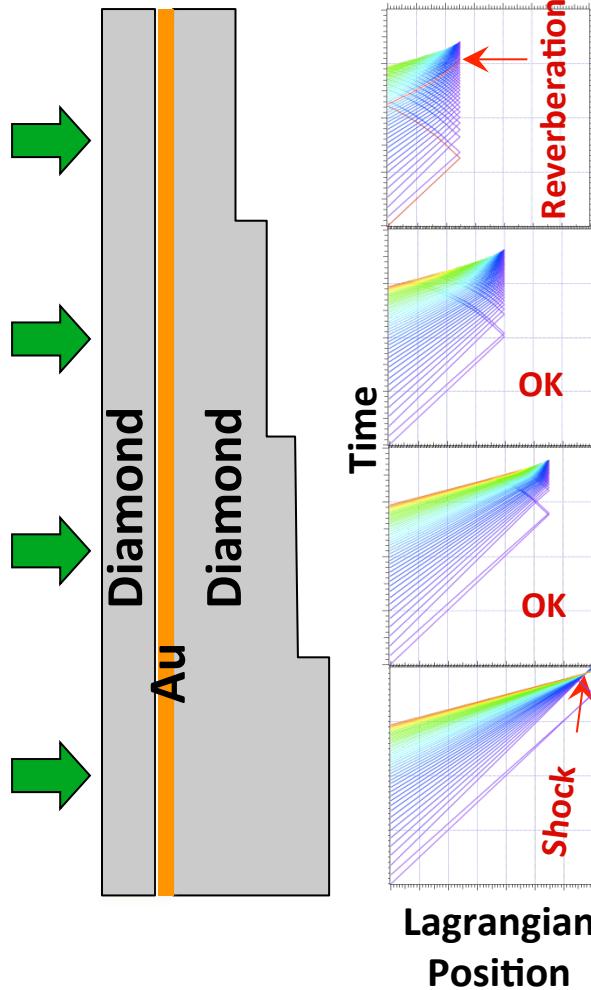
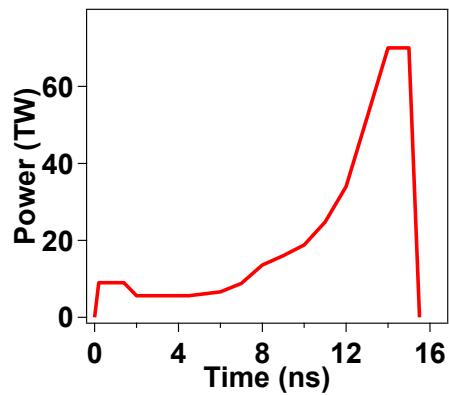
VISAR Streak Record



Free Surface Velocity Profiles



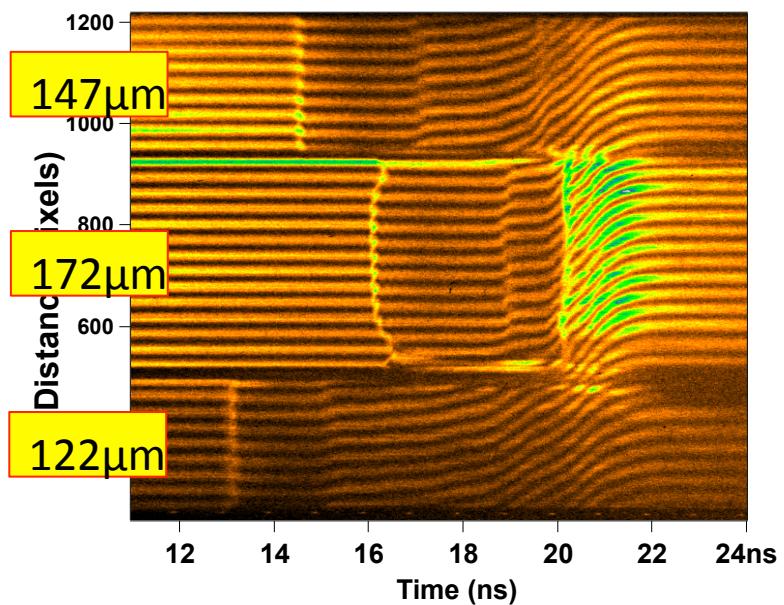
Design Constraints on Target and Pulse Shape



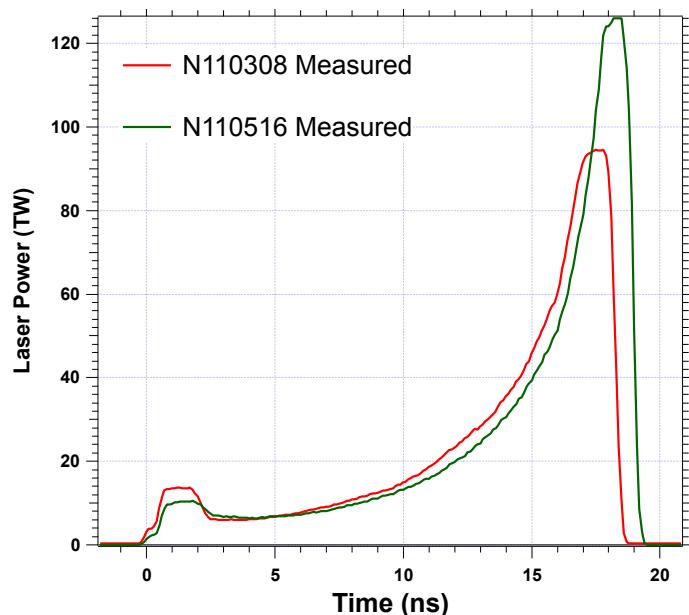
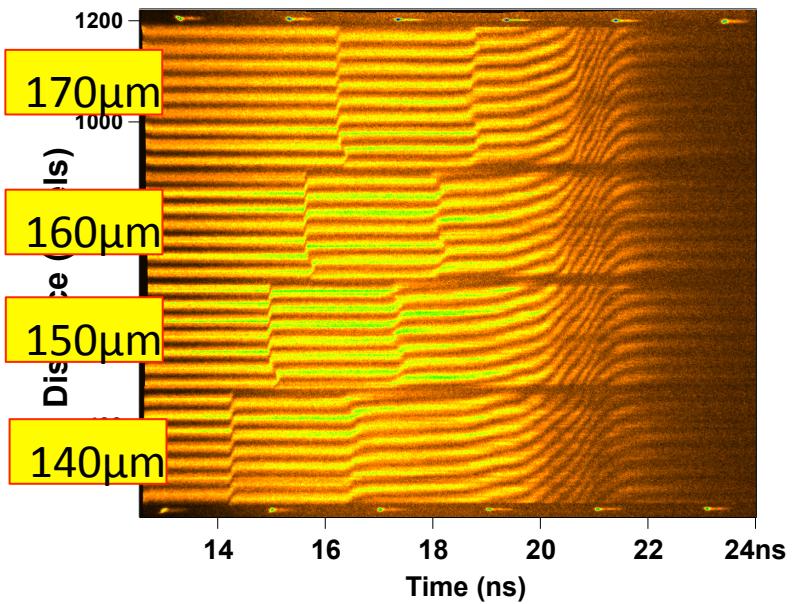
Design constraints:
No reverberation and no shock

Adjustments to Pulse Shaping: Initial shots

27 Mbar
N110308

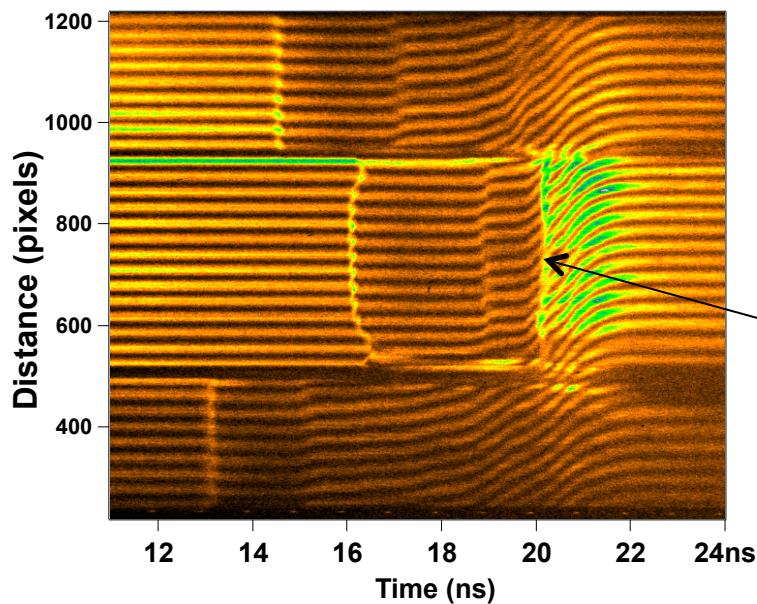


37 Mbar
N110516

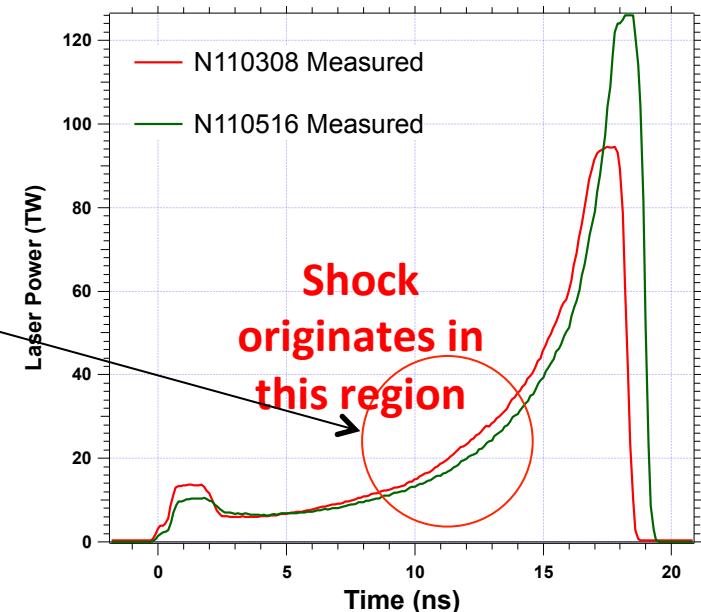
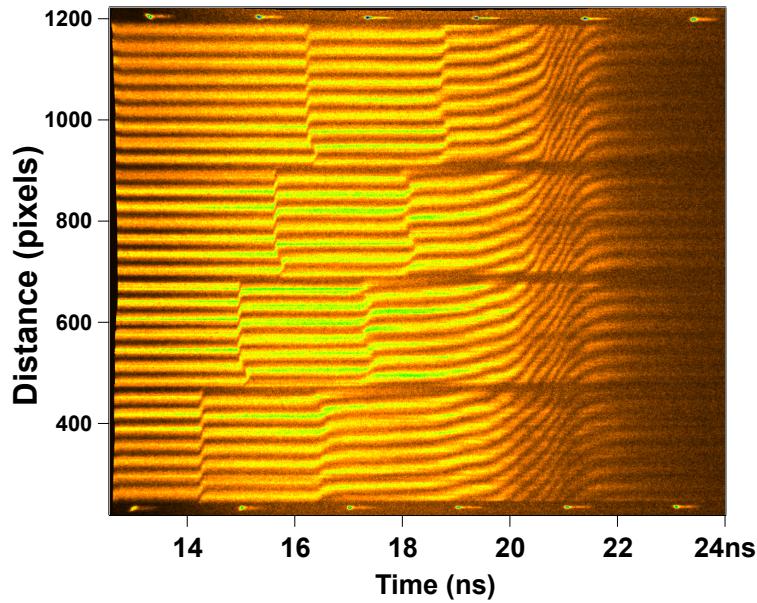


We were able to identify and correct regions responsible for growing shocks.

27 Mbar

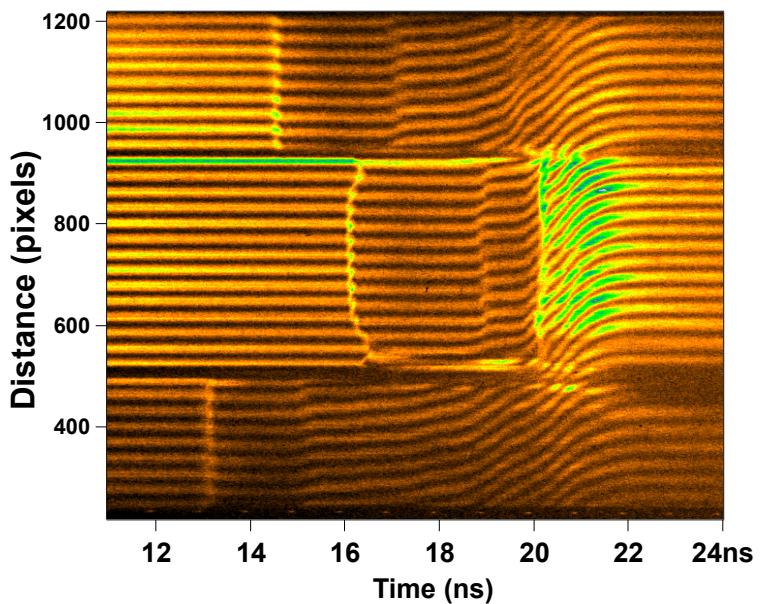


37 Mbar

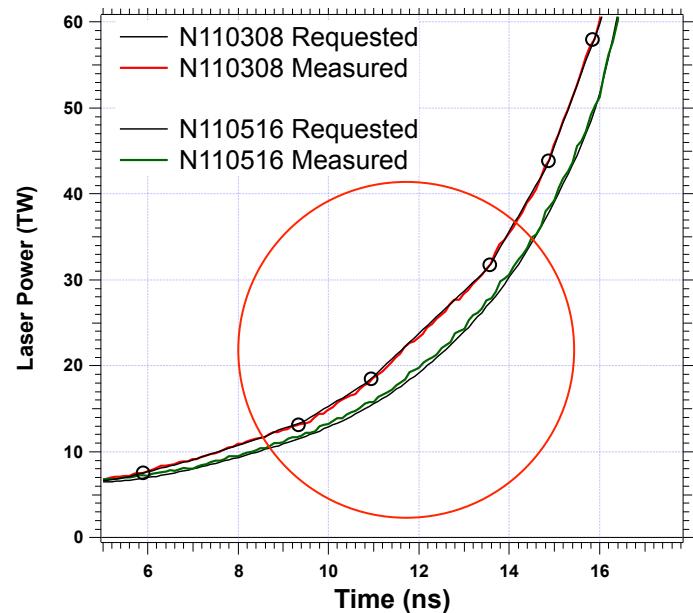
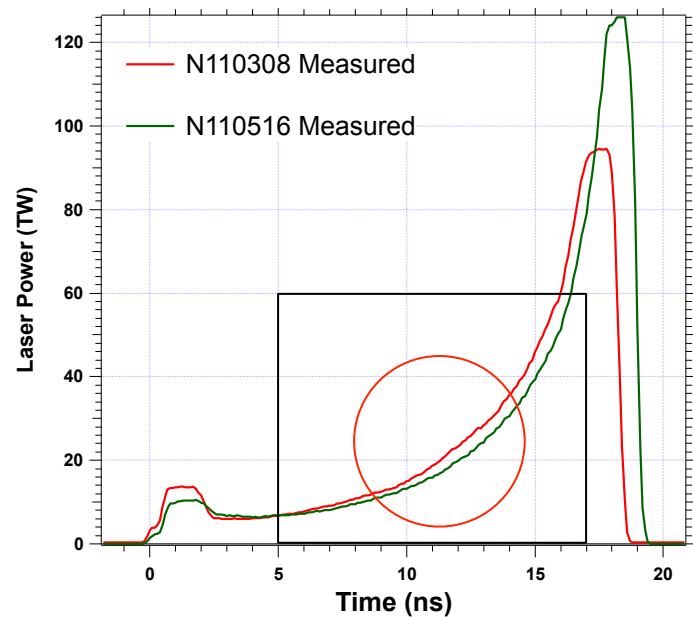
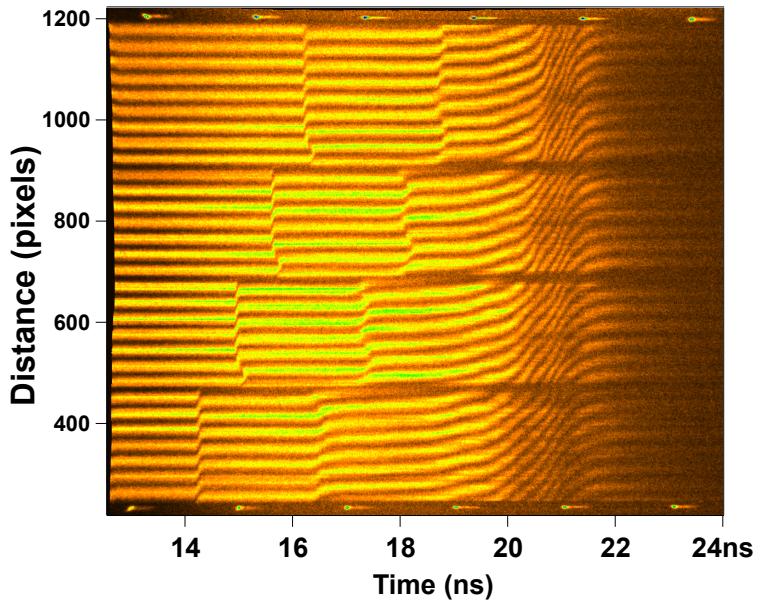


Pulse-shape correction worked extremely well

27 Mbar

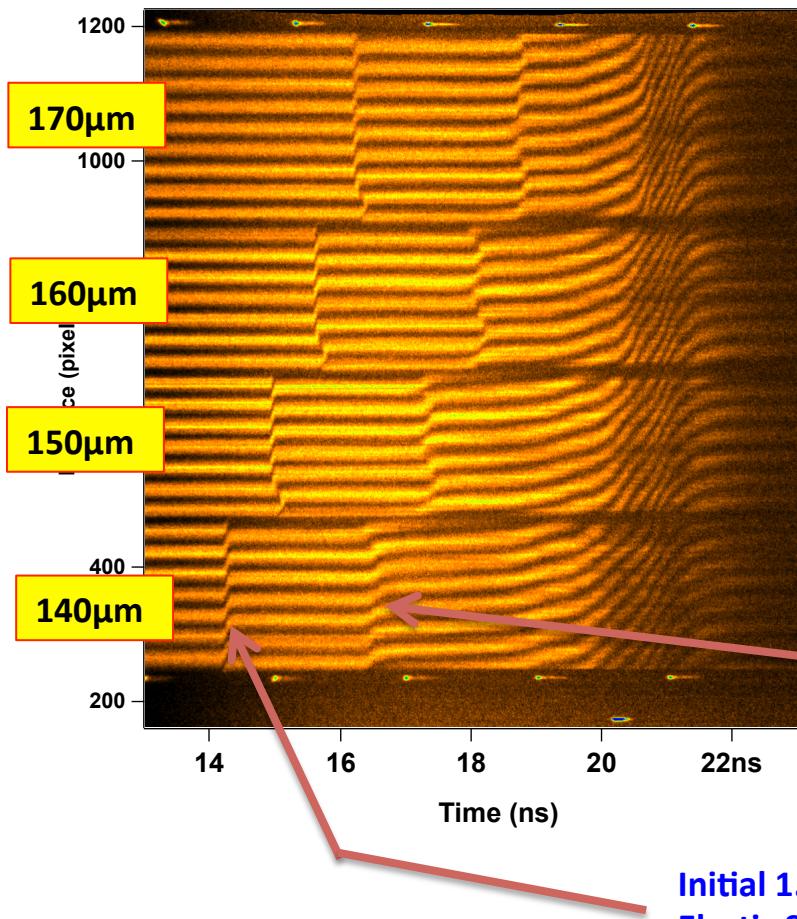


37 Mbar

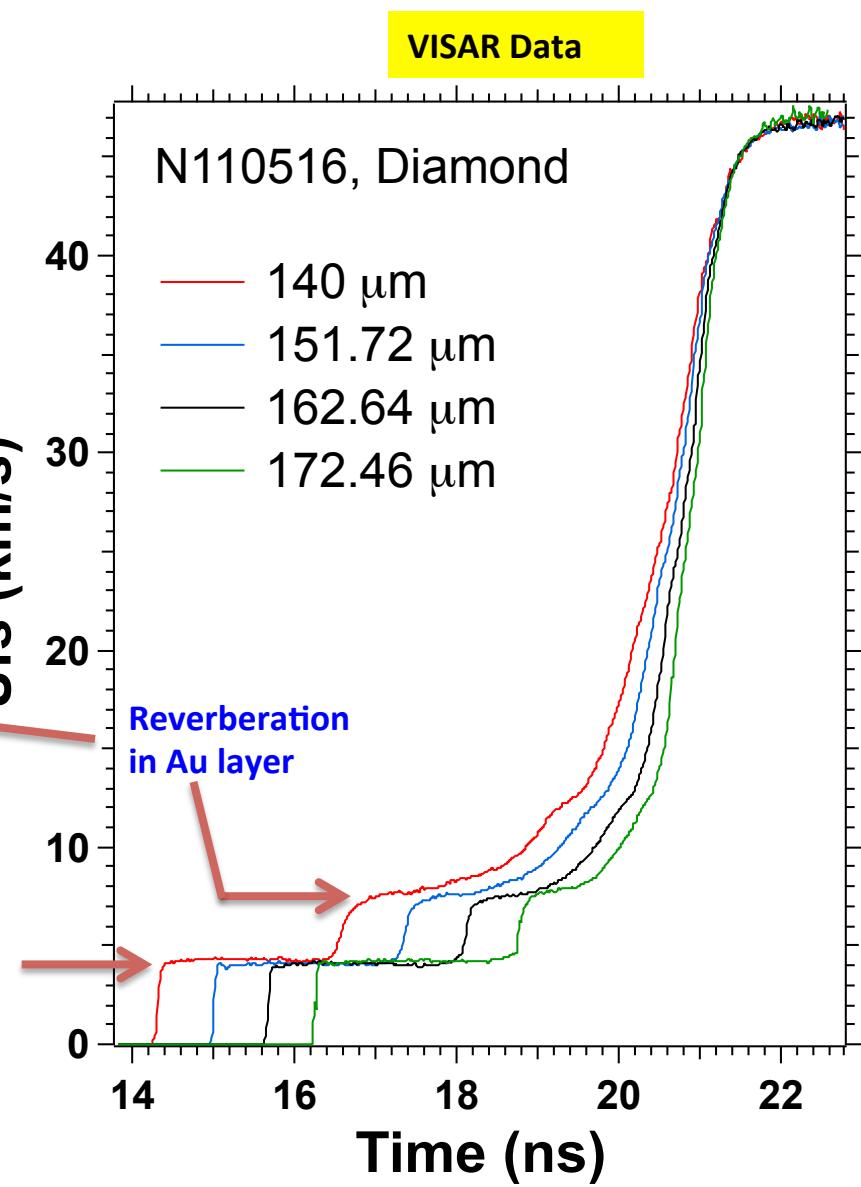


Diamond Ramp Compression: N110516

VISAR Streak Record

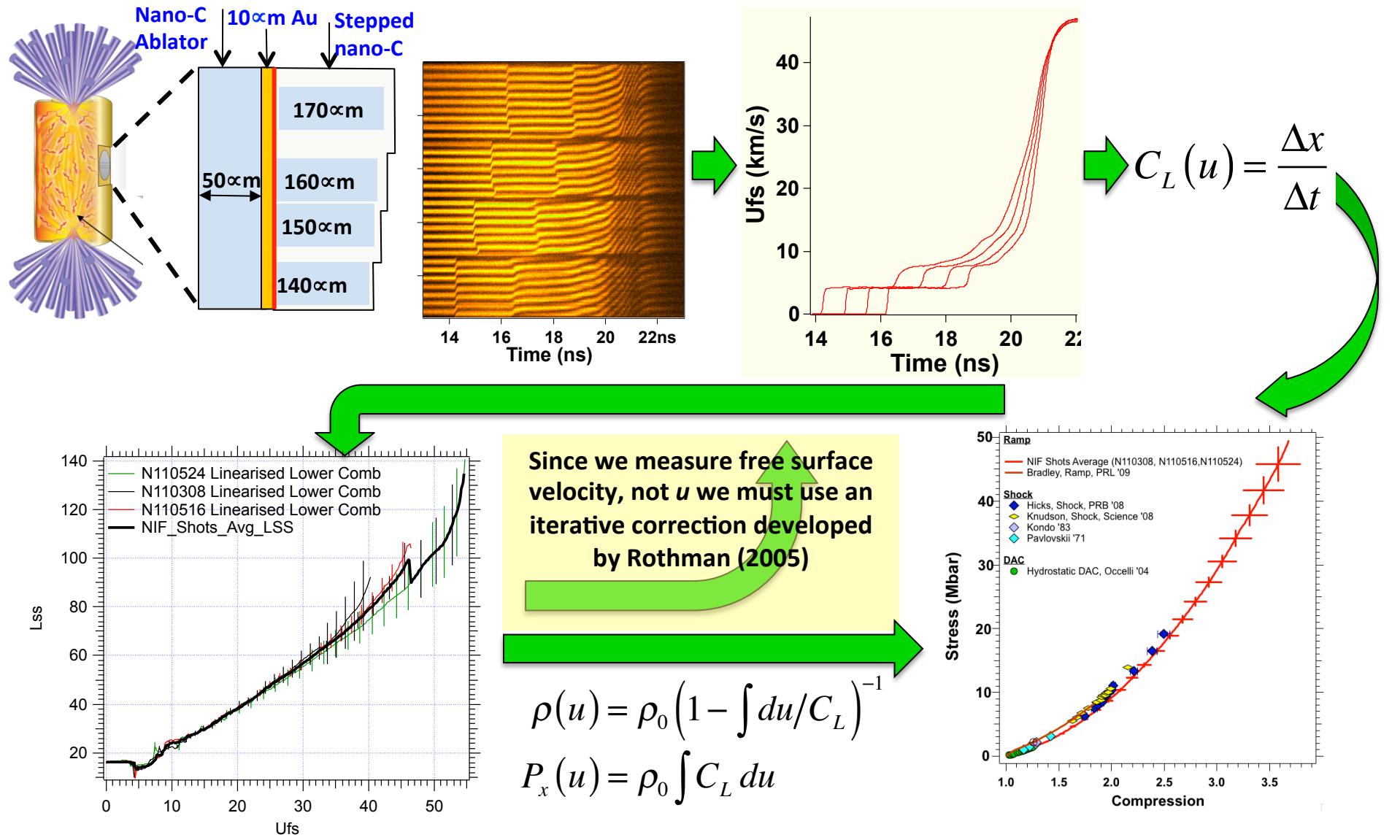


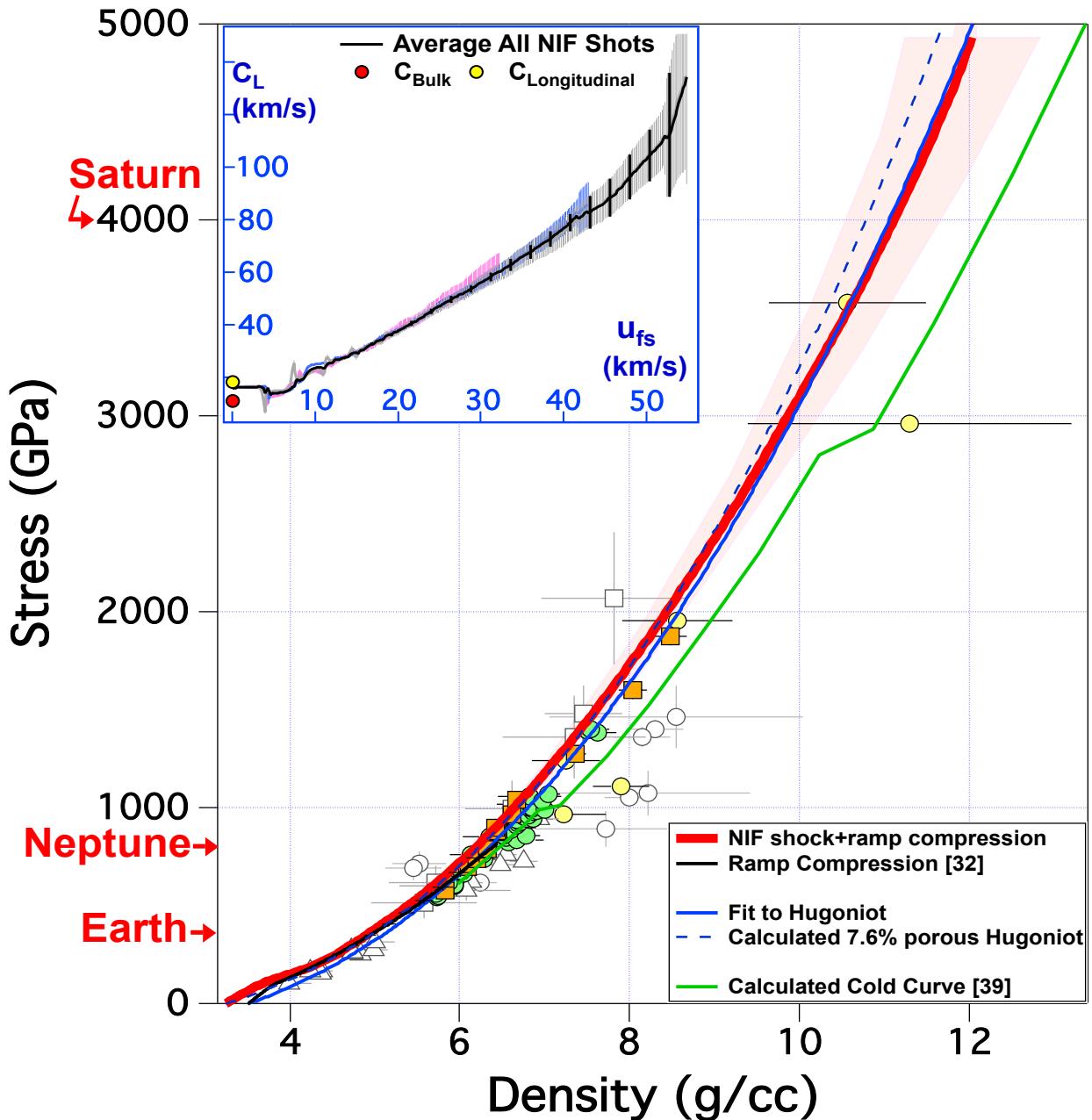
Free Surface Velocity Profiles



We use an Iterative Lagrangian Analysis to extract stress and density

(Rothman, et al., 2005)



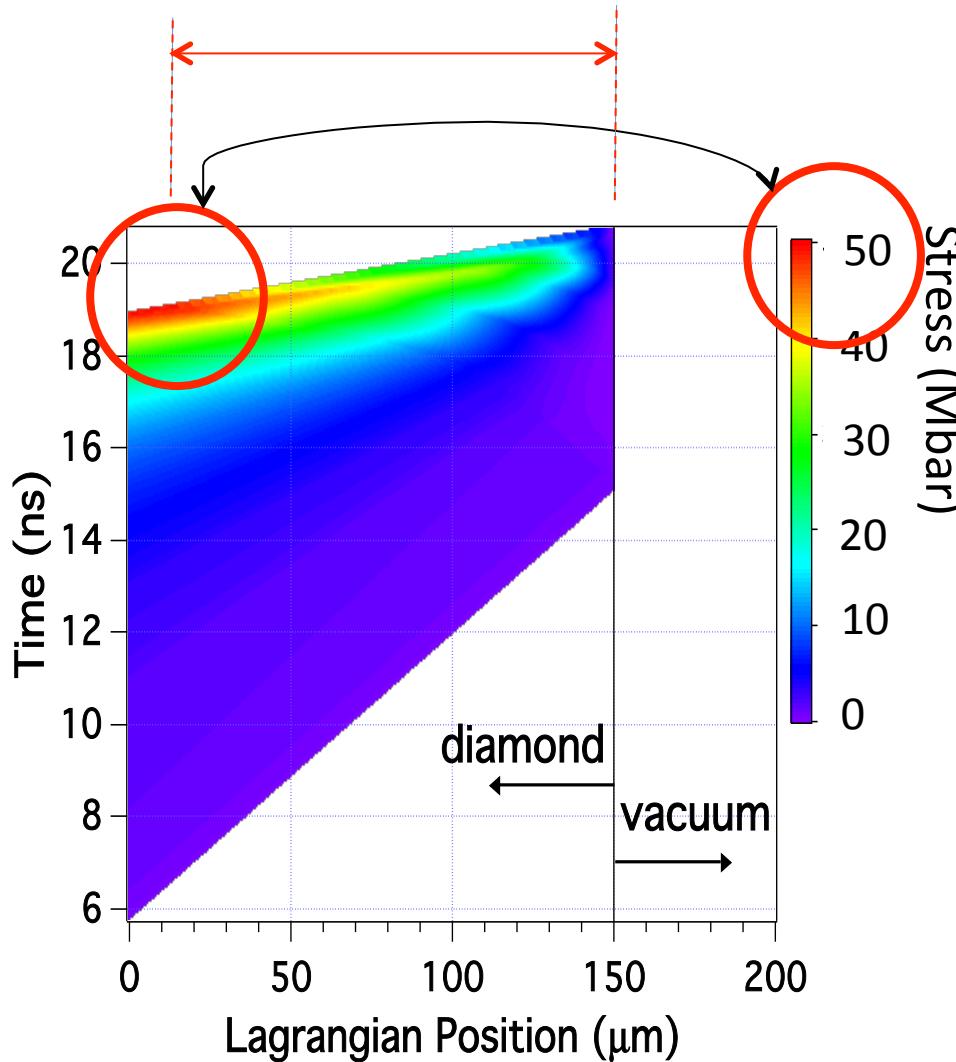


Main results

- Peak stress is 50 Mbar, greater than center of Saturn
- Diamond compressed by a factor of 3.7 to a density of around 12 gm/cm³
- Target reflectivity maintained to 50 Mbar

Temperature associated with ramp compression is impossible to quantify with standard pyrometric techniques

High Pressure region is located within the bulk of the material.

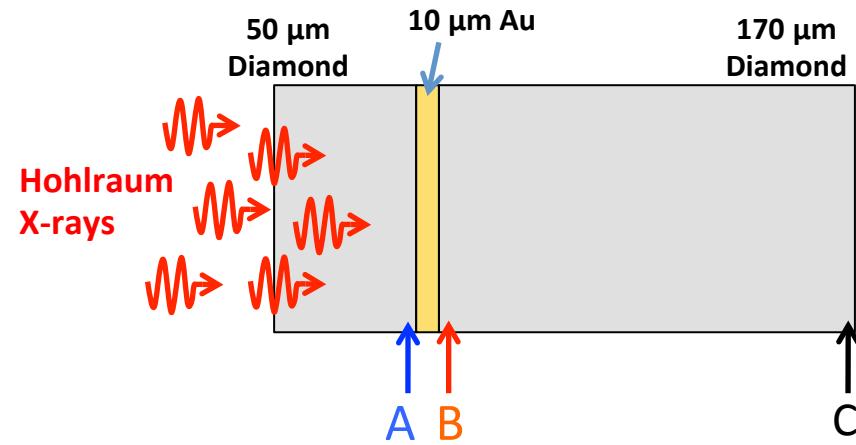


Potential Contributors to Sample Heating

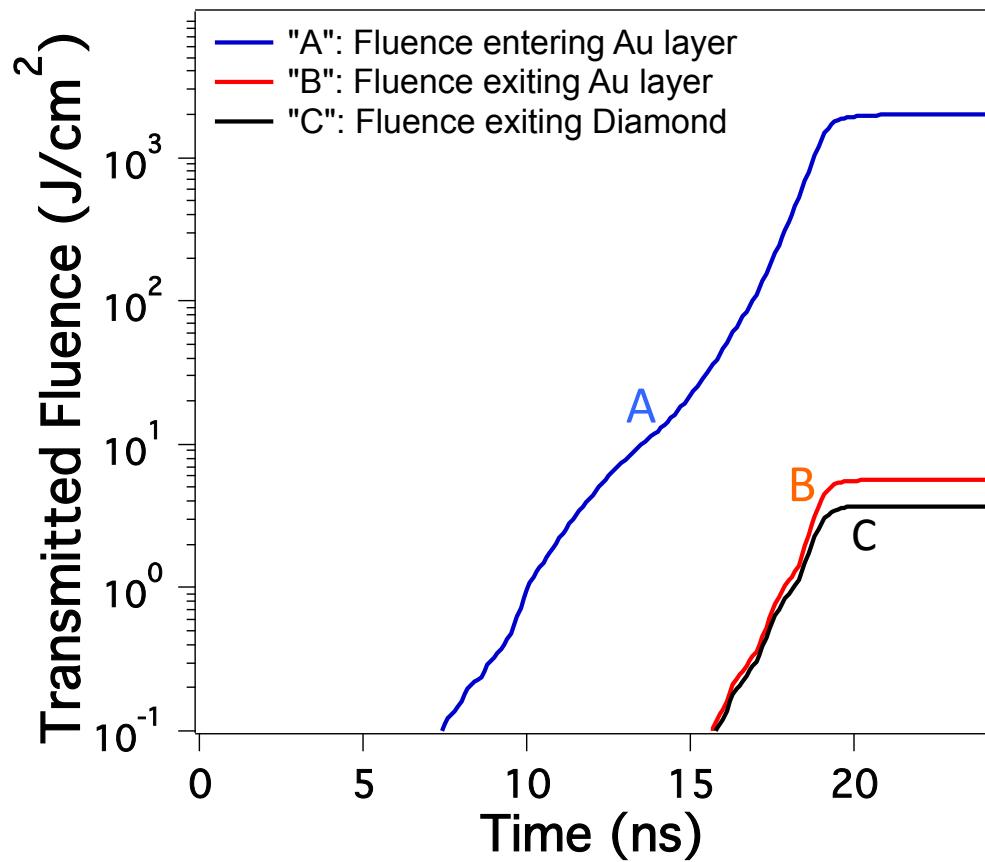
Radiation preheat

Plastic work

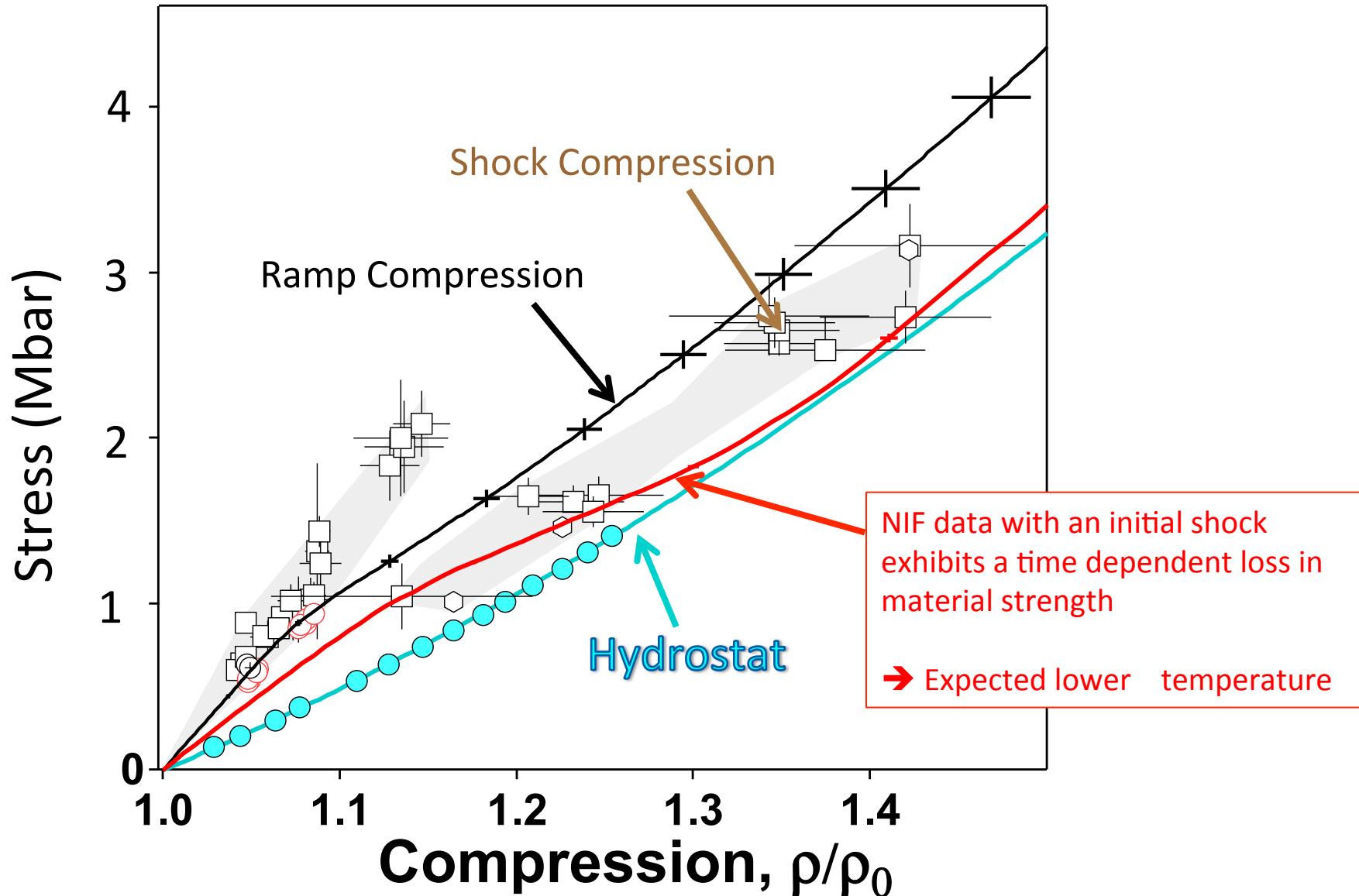
Radiation Preheat is calculated to be < 30 K



We calculated x-ray fluence integrated over 30eV-100keV at three different contours in the target: **A**, **B** and **C**



Work Heating due to material strength is reduced by initial shock compression



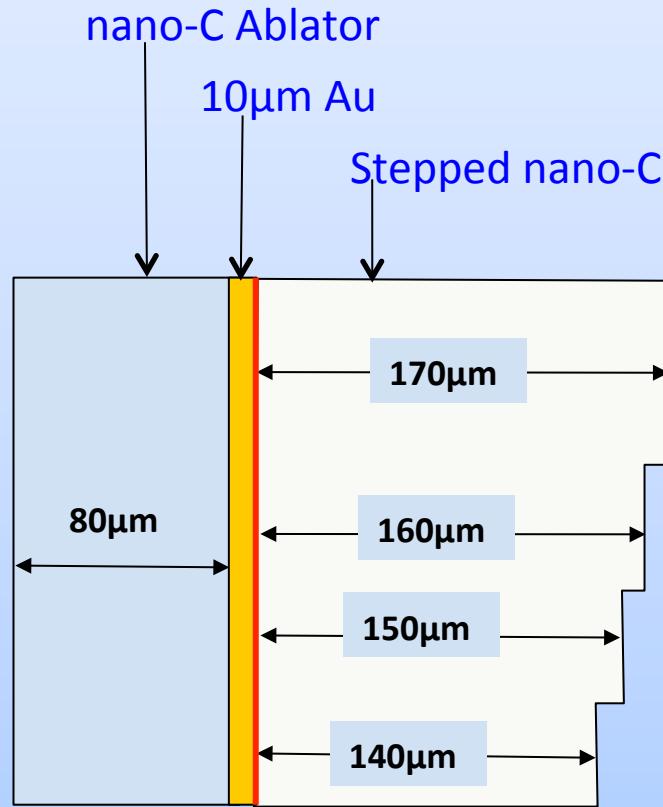
Summary

- Using National Ignition Facility (NIF), diamond has been compressed to conditions comparable to those found near the centers of Jupiter and Saturn.
- The measured compression behavior of diamond indicates that a peak stress near 5000 GPa and a 3.7-fold compression of this highly incompressible solid were achieved.
- Our samples appear to lose strength under compression helping to keep the temperature low. We see no evidence for any phase transitions or melting.
- Future work: 1) Extend to higher pressure; 2) Better understand effects of sample microstructure; 3) Additional diagnostics: X-ray Diffraction

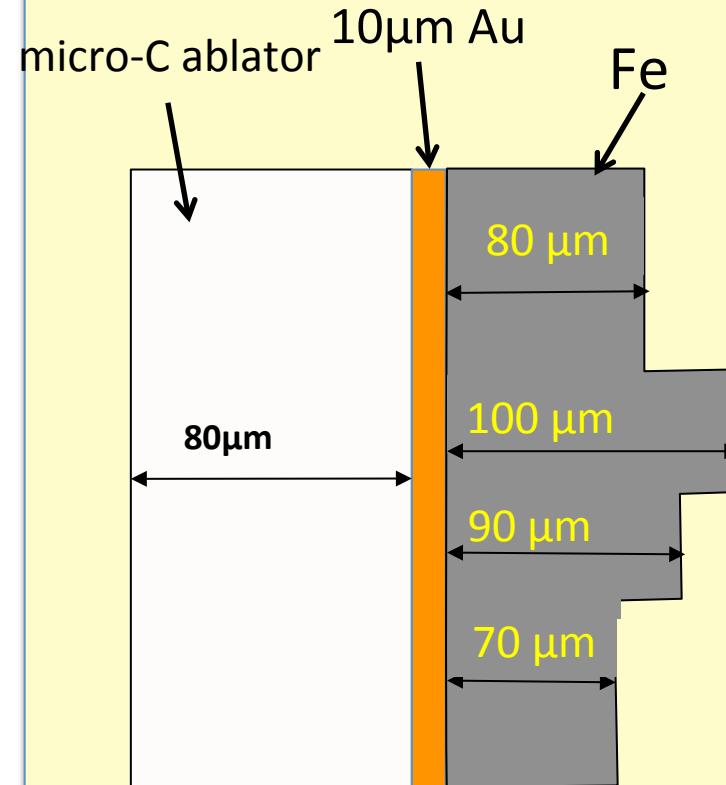
Plans for upcoming shots.....

Next Scheduled Shot Days: March 1 and 2

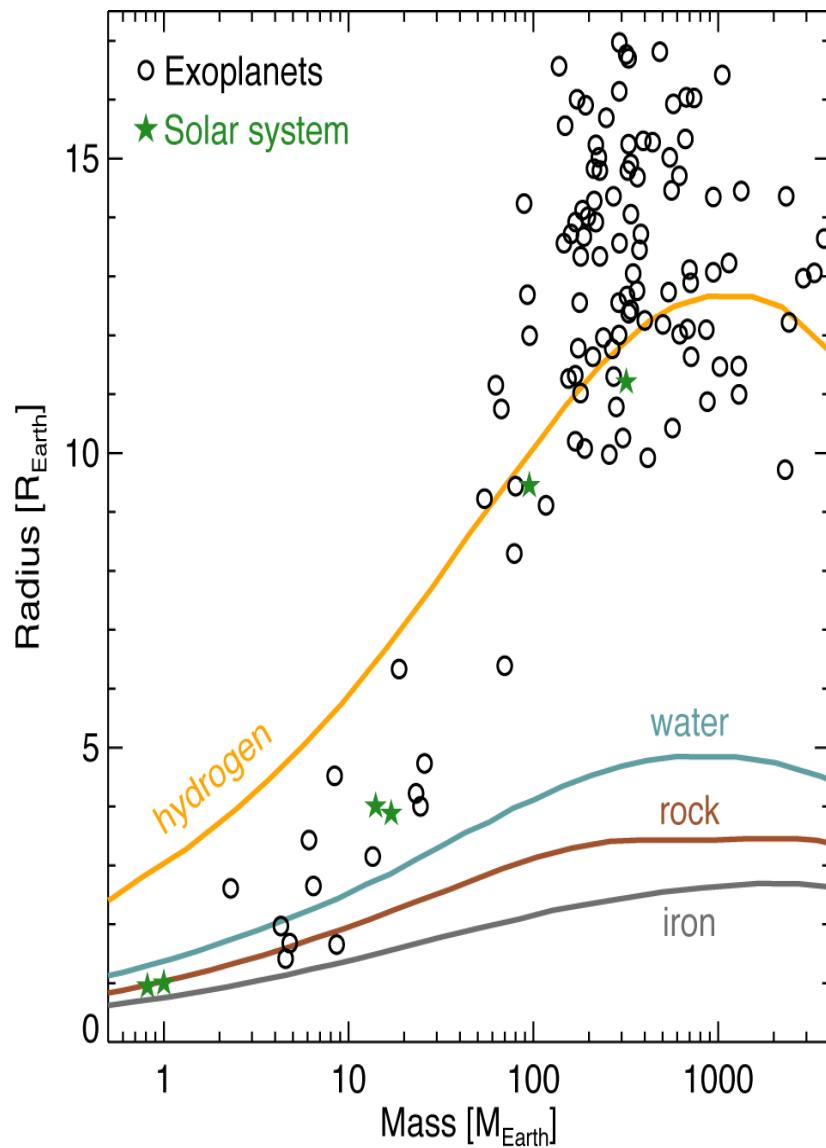
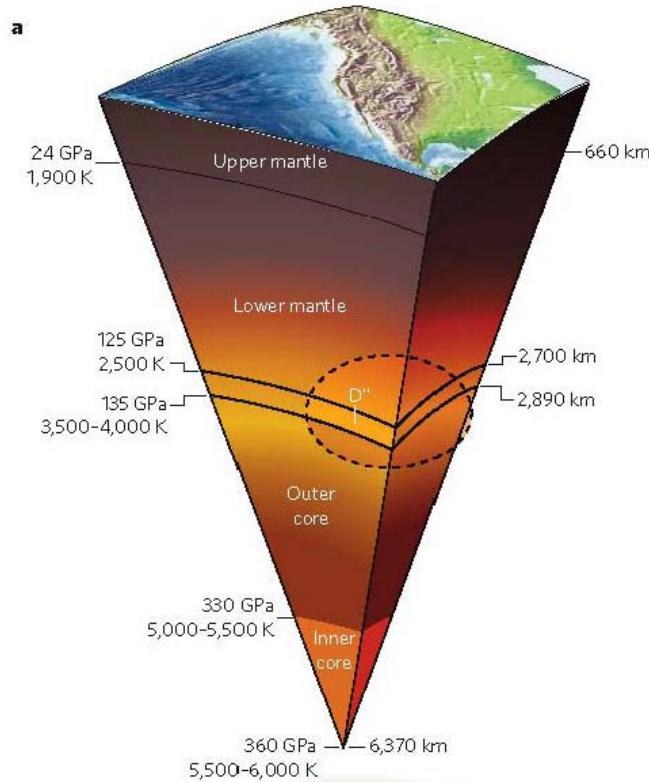
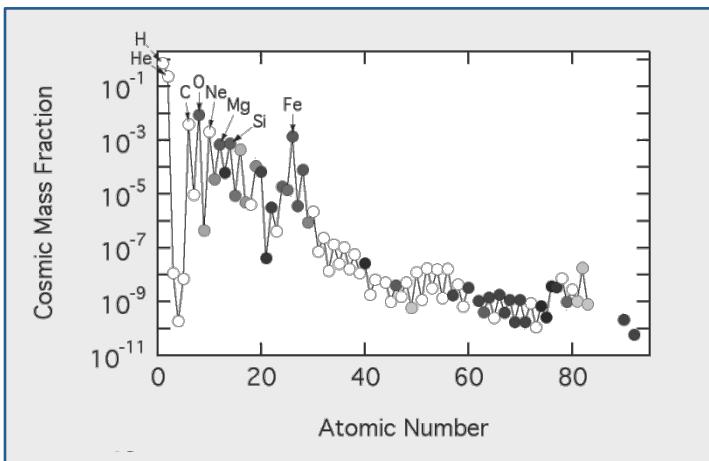
We will extend stress-density of Diamond to 100 Mbar



We will measure the stress-density response on Fe up to 20 Mbar



Fe and Fe alloys and Planetary cores



Winn et al., 2011

Iron and Extra-Solar Planets:

Super Earth

Super Mercury

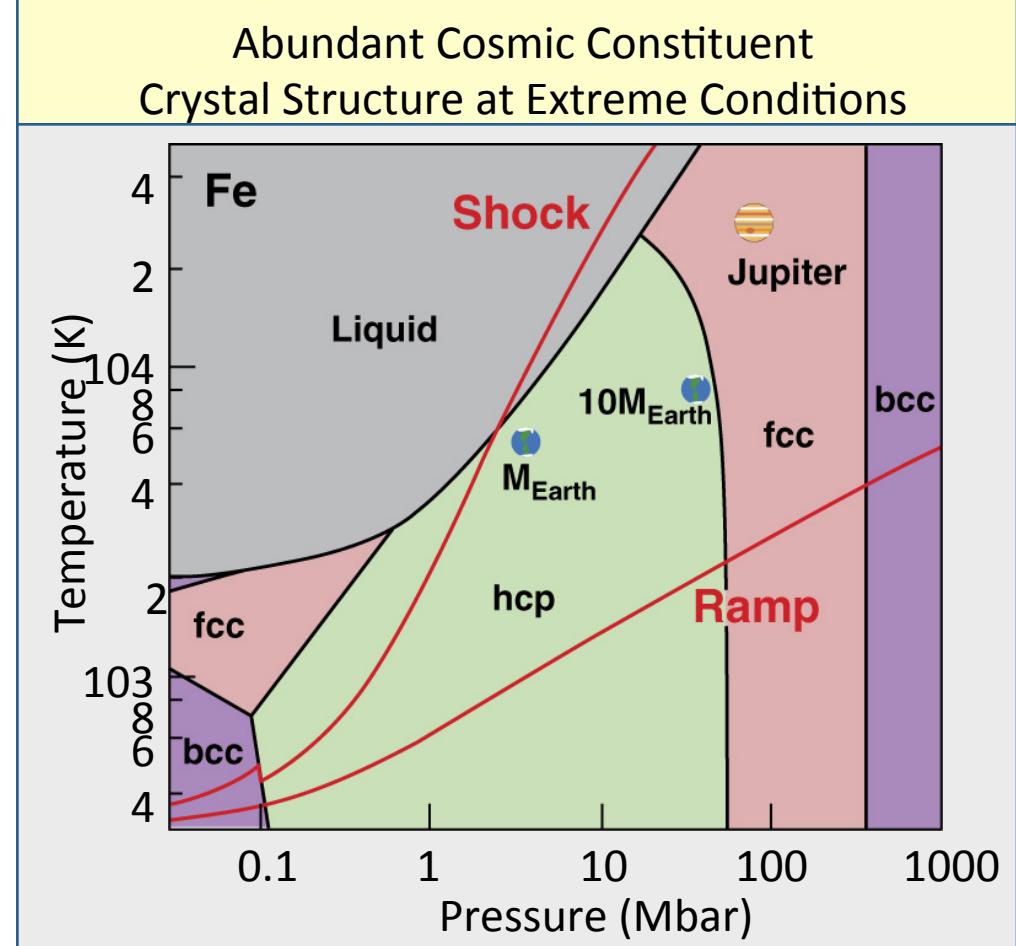
“Cannonball Planets”

Density:

Earth: 5.5 g/cm³

CoRoT-7b = 10.4 +/- 1.8 g/cm³

Kepler-10b = 8.8 +/- 2.5 g/cm³



L. Stixrude

	Mass (M _E)	Radius (R _E)	a (AU)	P _{central} (GPa)	T _{central} (K)
CoRoT-7b	7.4	1.6	0.02	4000	11,000
Kepler -10b	4.5	1.4	0.02	2500	8000

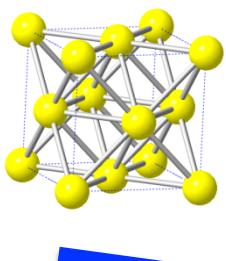
New experiments and theories point out surprising and decidedly complex behavior at the highest pressures considered.

Traditional view: All materials become simple at high pressure appears to be incorrect!

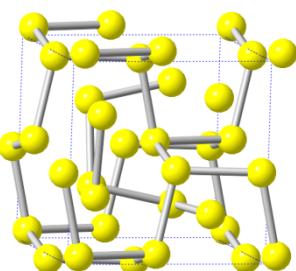
“... what the present results most assuredly demonstrate is the importance of pressure in revealing the limitations of previously hallowed models of solids”

—Neil Ashcroft (2009).

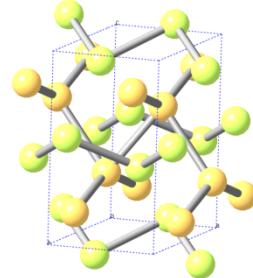
FCC, 65 GPa



cI16, 108 GPa

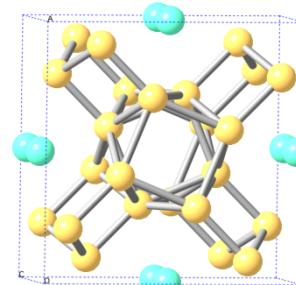


oP8, 119 GPa

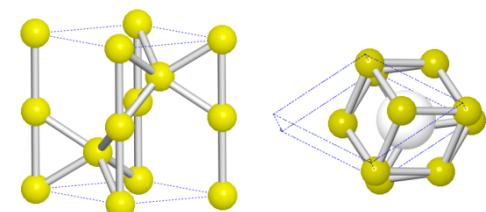


tI19, 147 GPa

Incommensurate

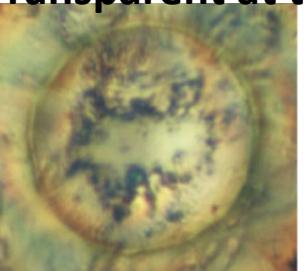


hP4, 190 GPa Insulating, Transparent Electride



Increasing Structural Complexity

Transparent at the highest pressures!



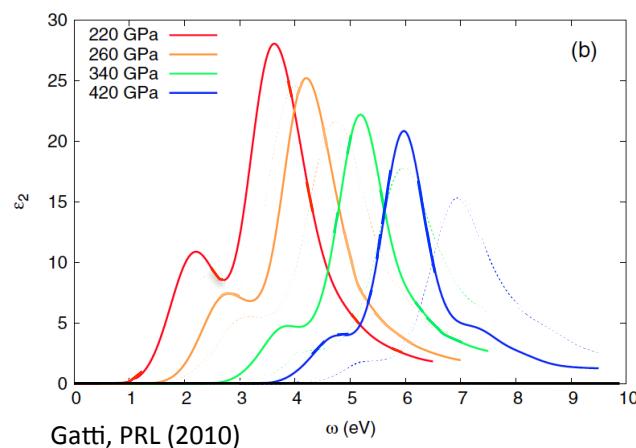
120 GPa



156 GPa



199 GPa Ma, Nature (2009)



Thank You!



